New Experiments with Antiprotons:

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY

Transforming Lives. Inventing the Future. www.iit.edu

Joint Experimental-Theoretical Seminar
Fermilab
20 February 2009

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New Directions in Hyperon, Charm, and Antimatter Physics

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Outline

(Varied menu!)

- Hyperon CP violation
- Low-energy antiprotons
- A new experiment
- Issues in charmonium
- Charm mixing
- Antihydrogen measurements
- Summary

Hyperon CP Violation?

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- An old topic:

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PHYSICAL REVIEW VOLUME 184, NUMBER 5 25 AUGUST 1969

Final-State Interactions in Nonleptonic Hyperon Decay

O. E. OVERSETH*
The University of Michigan, Ann Arbor, Michigan 48104

AND

S. PAKVASA†
University of Hawaii, Honolulu, Hawaii 96822
(Received 1 April 1969)

⋮

E. Tests for *CP* and *CPT* Invariance

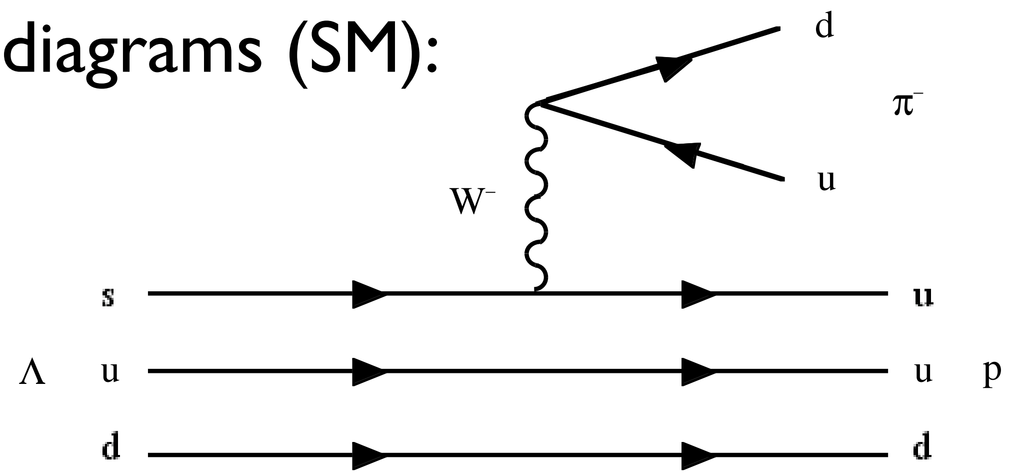
Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta} \neq -\beta$.

Also, as usual, *CPT* invariance implies equality of Λ^0 and $\bar{\Lambda}^0$ lifetimes, whereas *CP* invariance implies equality of partial rates $\Gamma^0 = \bar{\Gamma}^0$, and $\Gamma^- = \bar{\Gamma}^+$. This is also true when final-state interactions are included in the analysis.

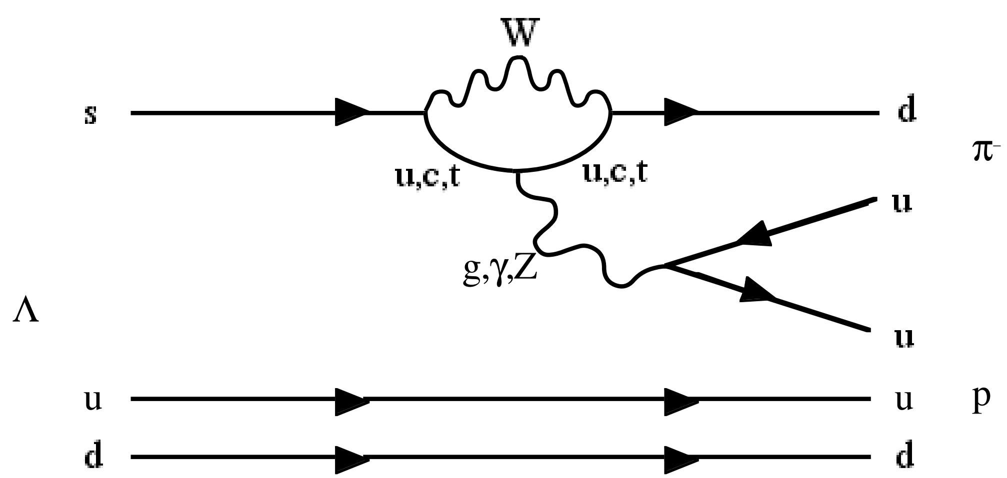
Hyperon CP Violation?

- Example Feynman diagrams (SM):

Λ decay:



Λ penguin decay:



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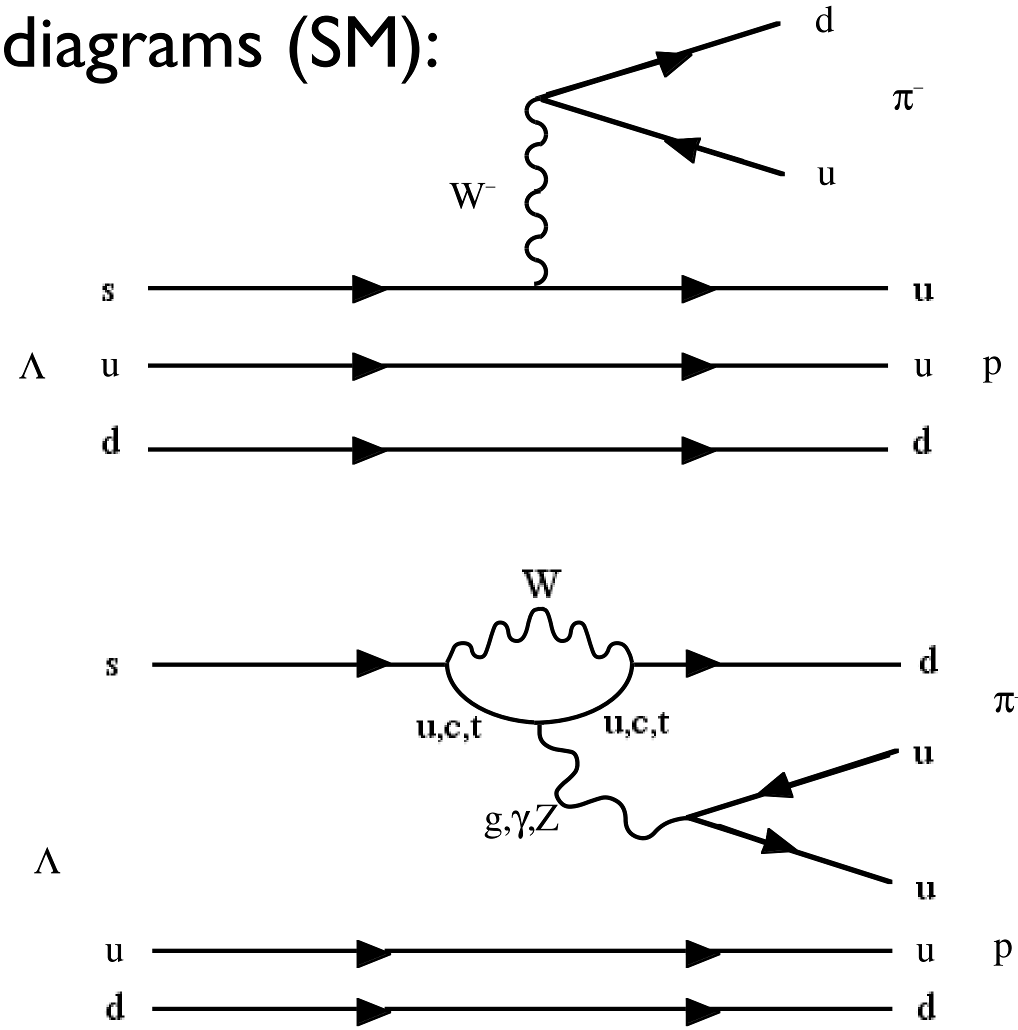

- New Physics (SUSY, etc.) could also contribute!

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- CP-odd observables:

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  - Decay amplitude for ΔS = 1 decay of spin-1/2 strange baryon into spin-1/2 baryon and meson (e.g., $\Lambda \to p\,\pi^-$):

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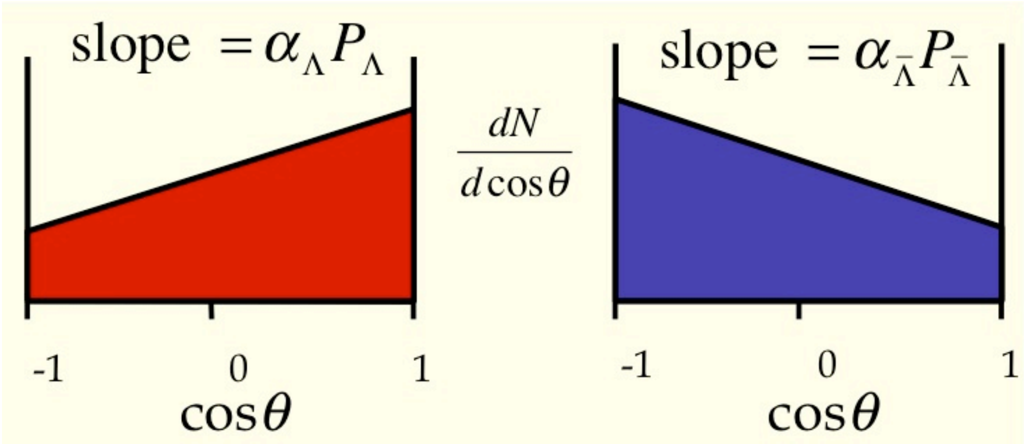

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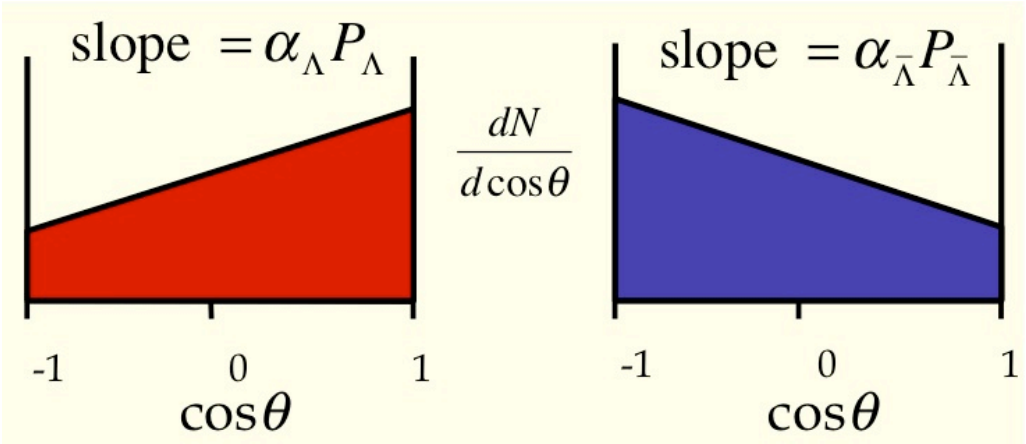

- *CP* conserved ⇔ slope = – $\overline{\text{slope}}$

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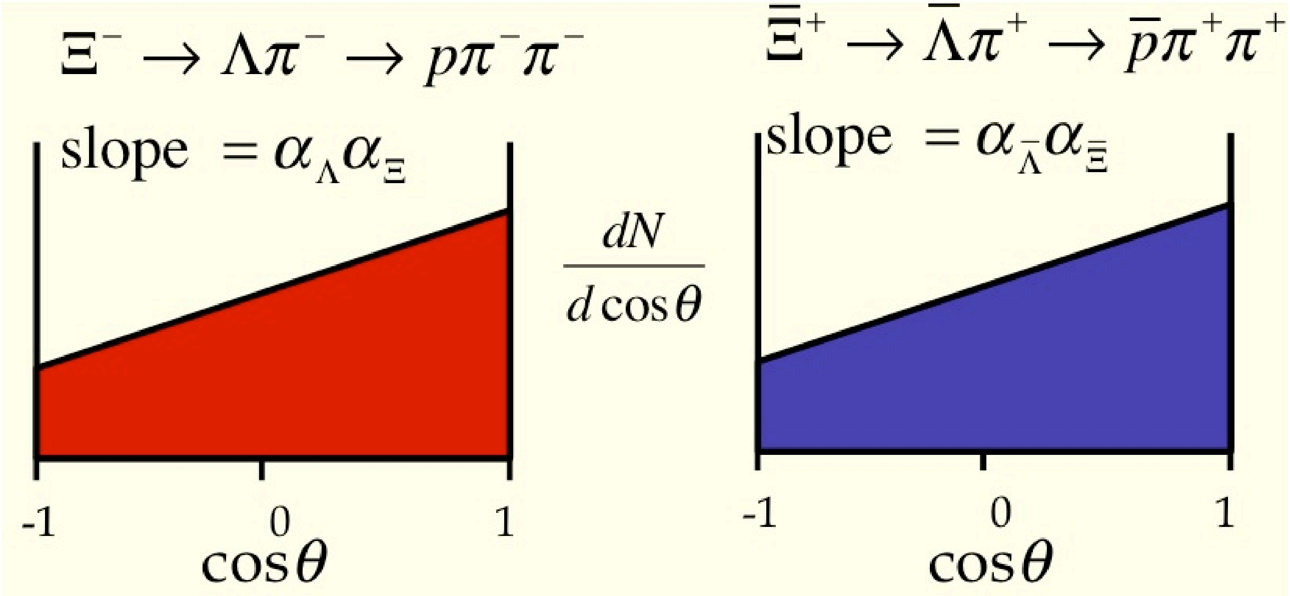
➡HyperCP "trick": $\Xi^- \to \Lambda\pi^-$ decay gives $P_\Lambda = -P_{\bar{\Lambda}}$



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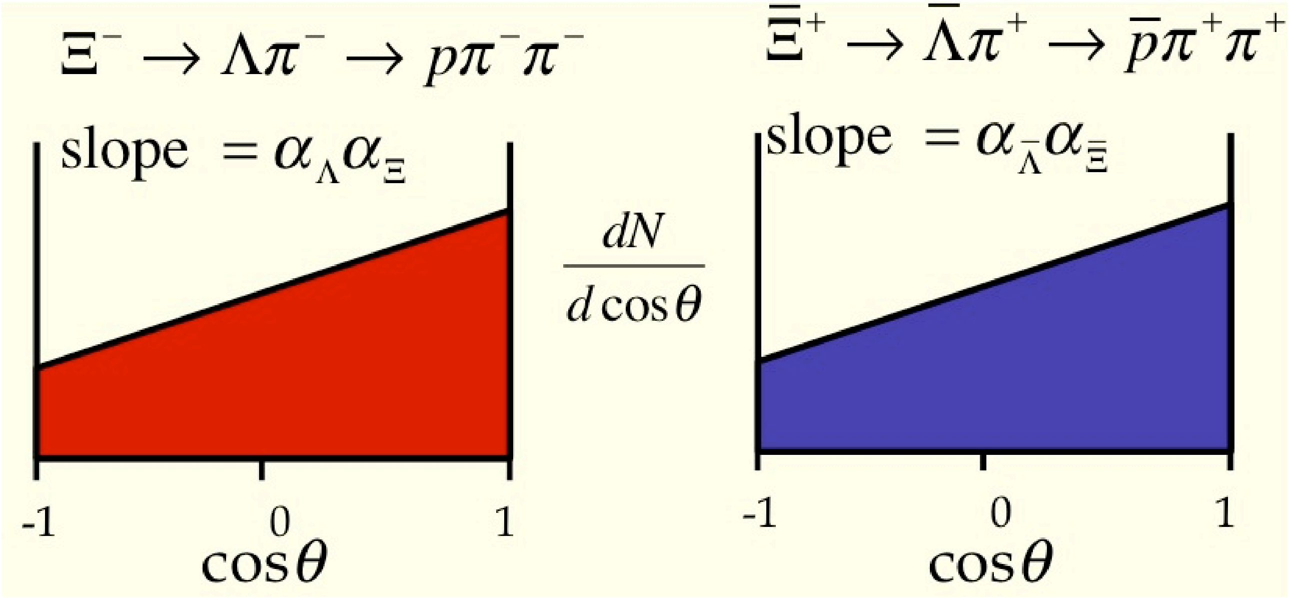

- Unequal slopes $\Rightarrow$ *CP* violated!

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Theory [Donoghue, He, Pakvasa, Valencia, et al., e.g., PRL 55, 162 (1985); PRD 34, 833 (1986); PLB 272, 411 (1991)]

- SM: $A_\Lambda \sim 10^{-5}$, $|A_{\Xi\Lambda}| < 5 \times 10^{-5}$ [J. Tandean, G. Valencia, Phys. Rev. D 67, 056001 (2003)]
- Other models: $\mathcal{O}(10^{-3})$
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R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 $\pm$ 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 $\pm$ 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
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E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

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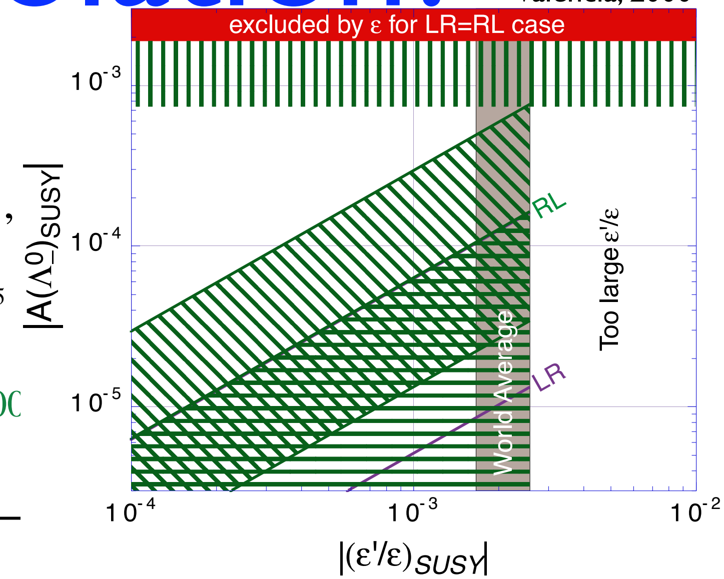

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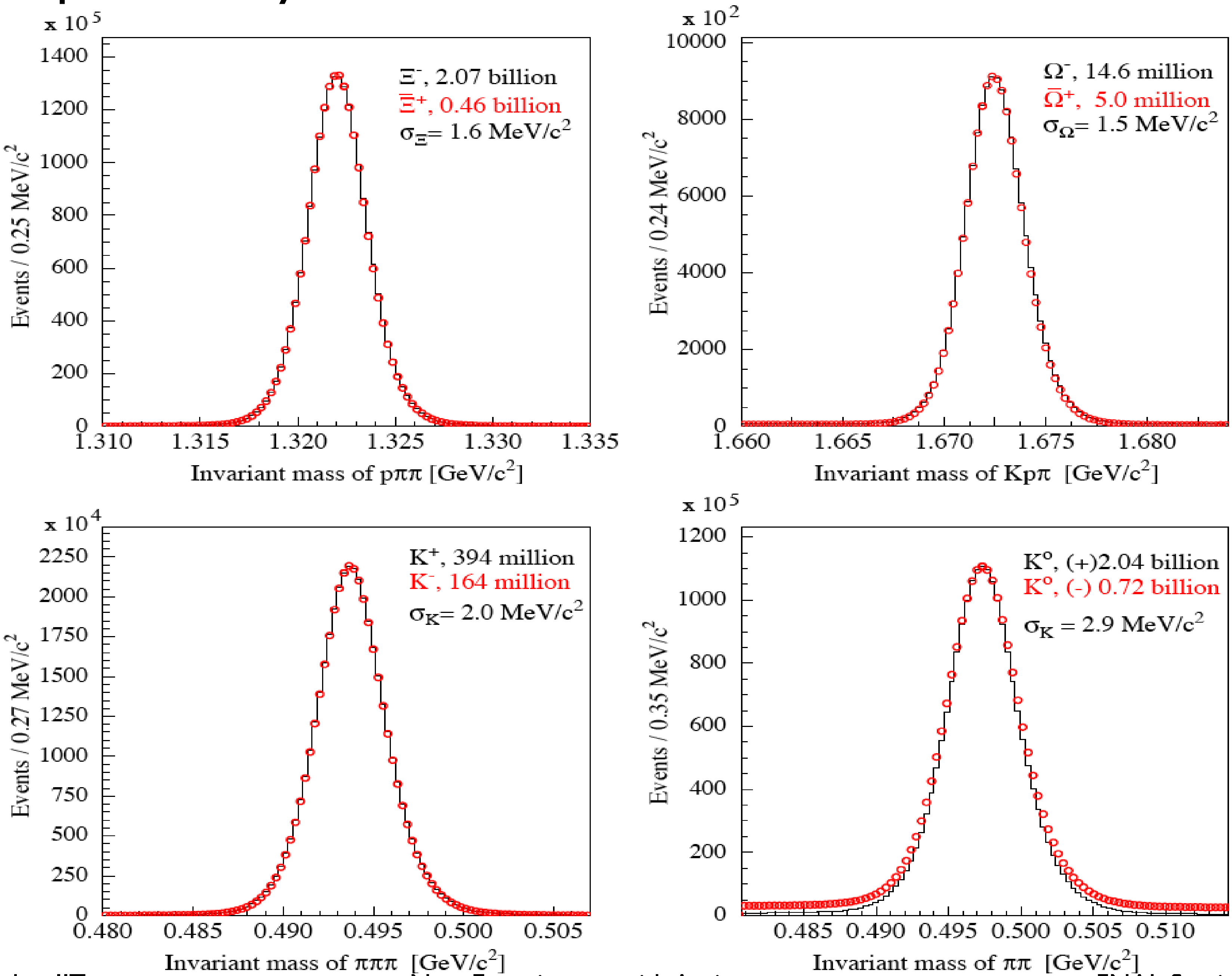

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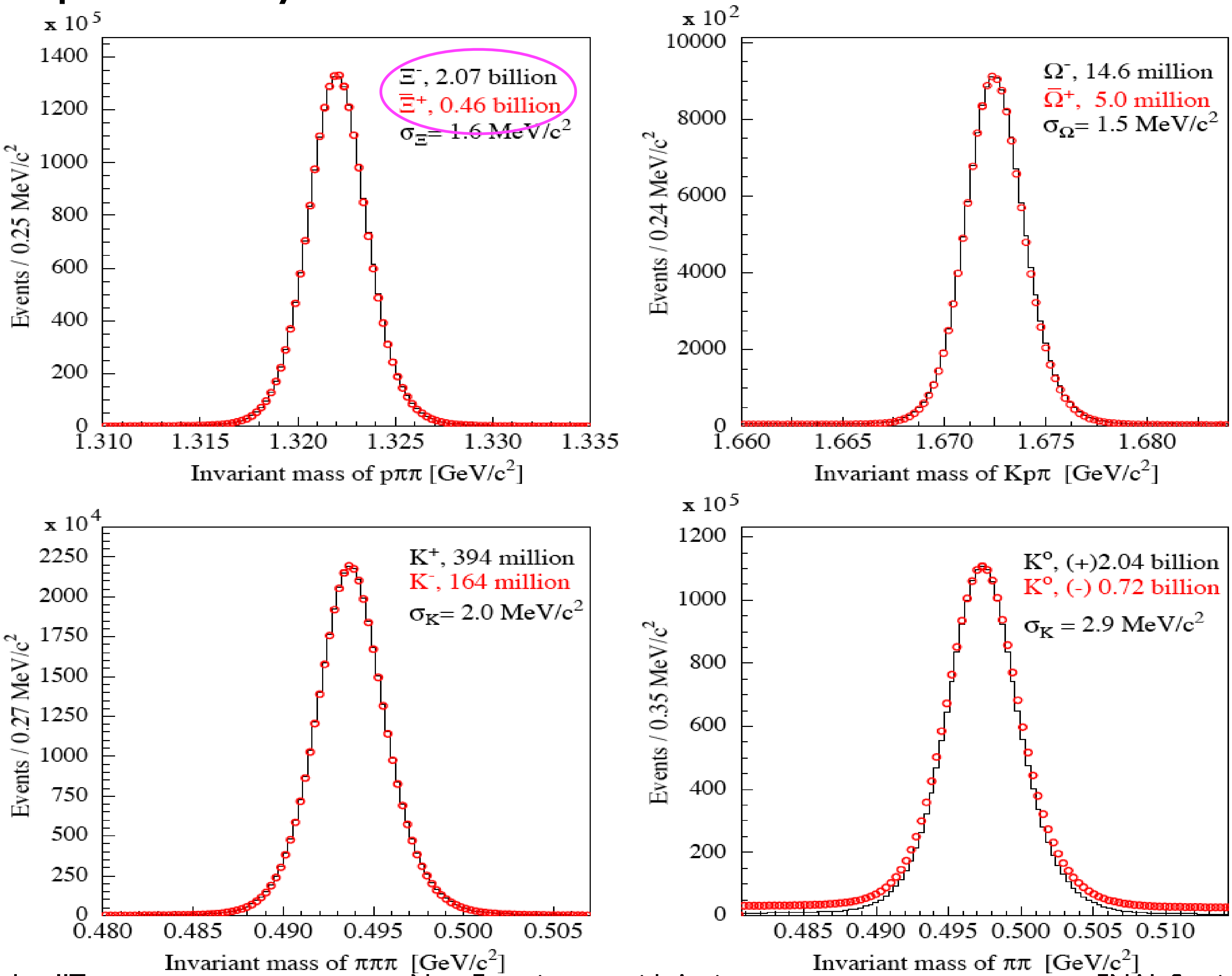

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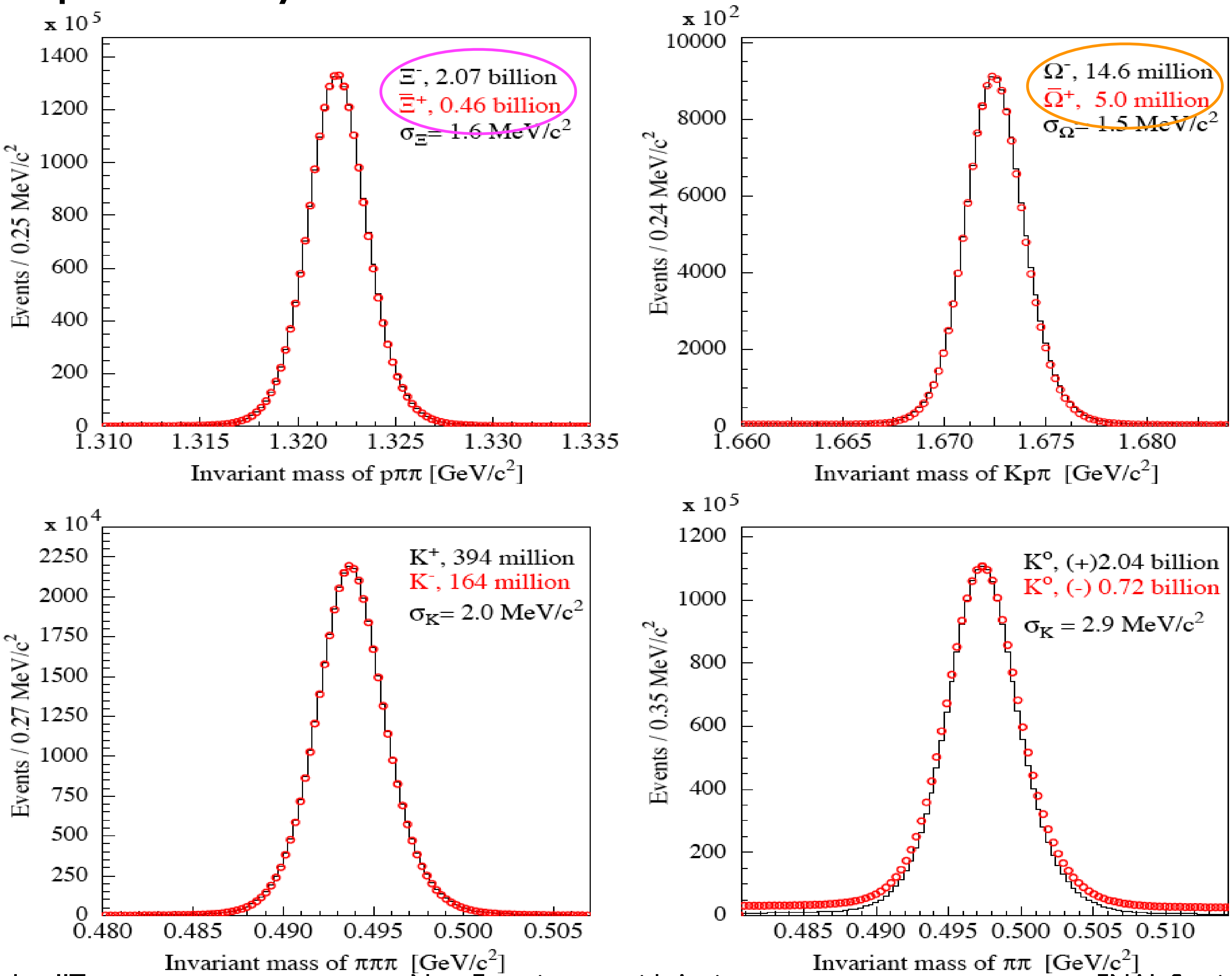
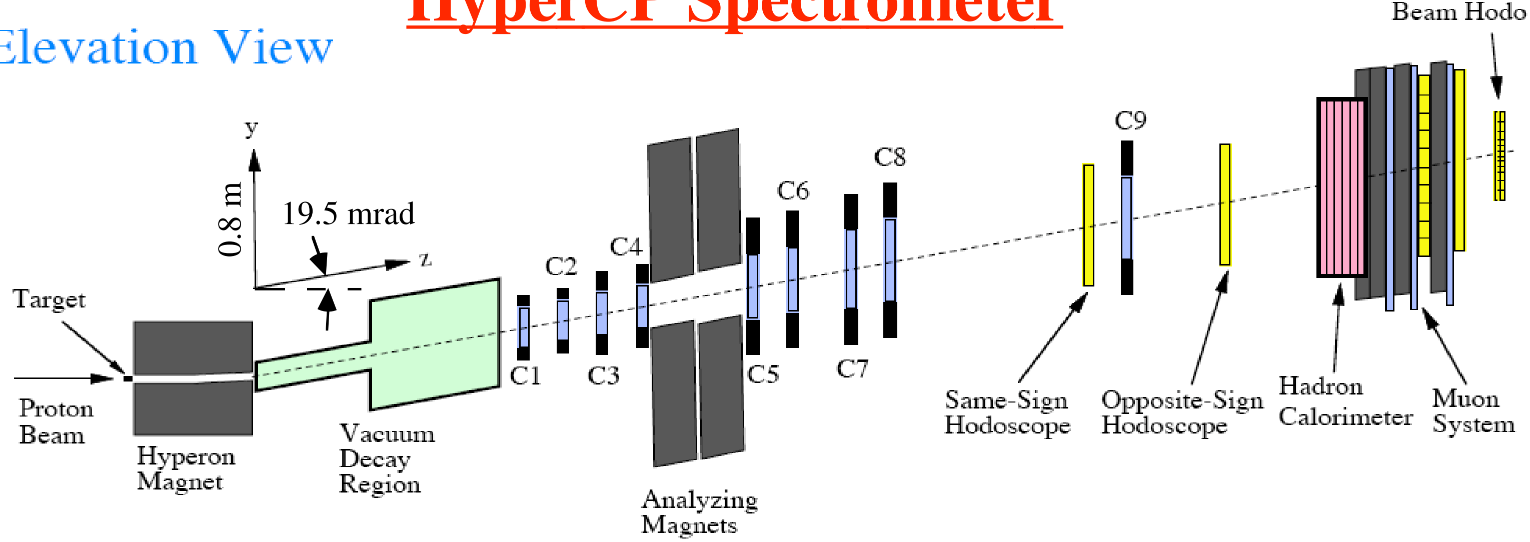
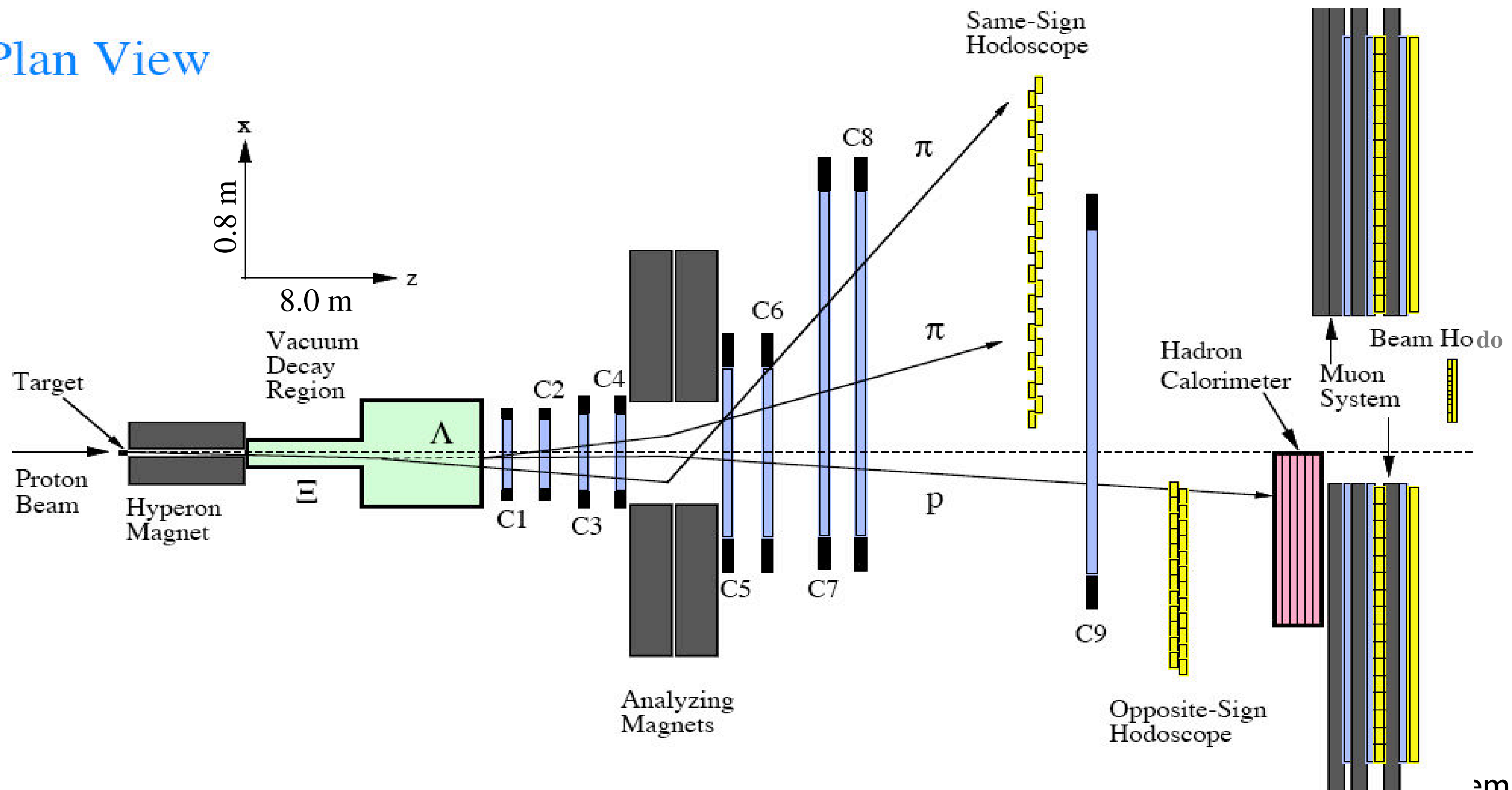


HyperCP Spectrometer

Elevation View



Plan View



...and Fast HyperCP DAQ System

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≈20,000 channels of MWPC latches

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...written to 32 tapes in parallel

HyperCP Collaboration

A. Chan, Y.-C. Chen, C. Ho, P.-K. Teng
Academia Sinica, Taiwan

K. Clark, M. Jenkins
University of South Alabama, USA

W.-S. Choong, Y. Fu, G. Gidal, T. D. Jones, K.-B. Luk*, P. Gu, P. Zyla
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R. Burnstein, A. Chakravorty, D. Kaplan, L. Lederman, D. Rajaram, H. Rubin, N. Solomey, C. White
Illinois Institute of Technology, USA

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University of Lausanne, Switzerland

H. R. Gustafson, M. Longo, F. Lopez, H. Park
University of Michigan, USA

E. C. Dukes*, C. Durandet, T. Holmstrom, M. Huang, L. C. Lu, K. S. Nelson
University of Virginia, USA

*co-spokespersons

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- $\Sigma^+ \to p\mu^+\mu^-$: smallest baryon BR ever seen!

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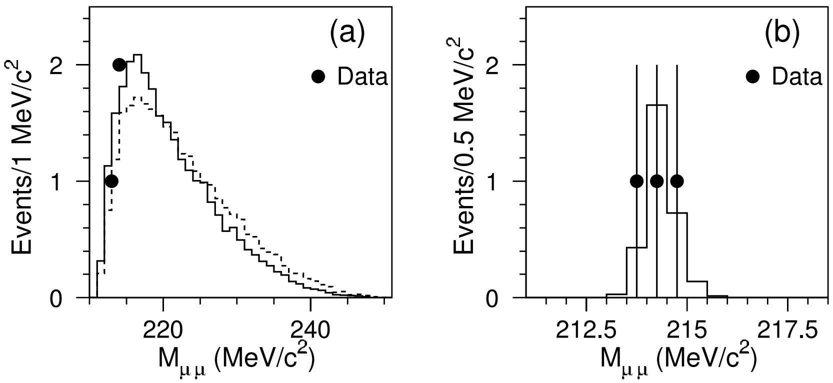

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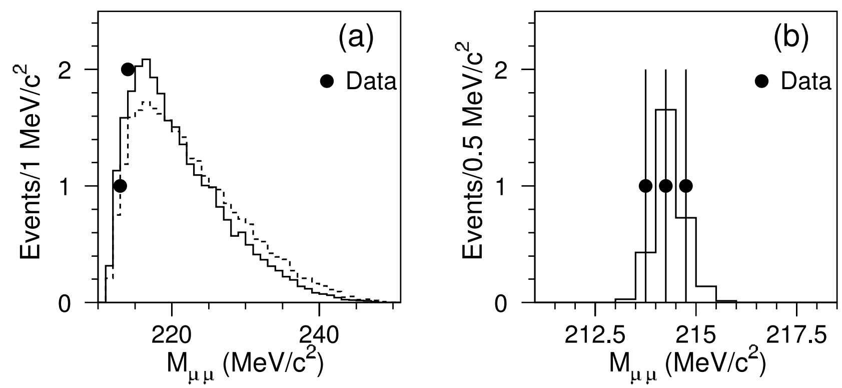

≈2.4σ fluctuation of SM

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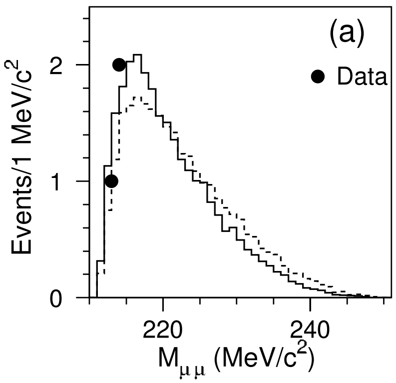

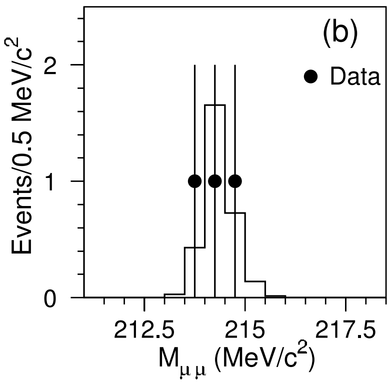

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- SUSY Sgoldstino?
- SUSY light Higgs?

PRL **98,** 081802 (2007) PHYSICAL REVIEW LETTERS week ending 23 FEBRUARY 2007

Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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(Received 2 November 2006; published 22 February 2007)

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Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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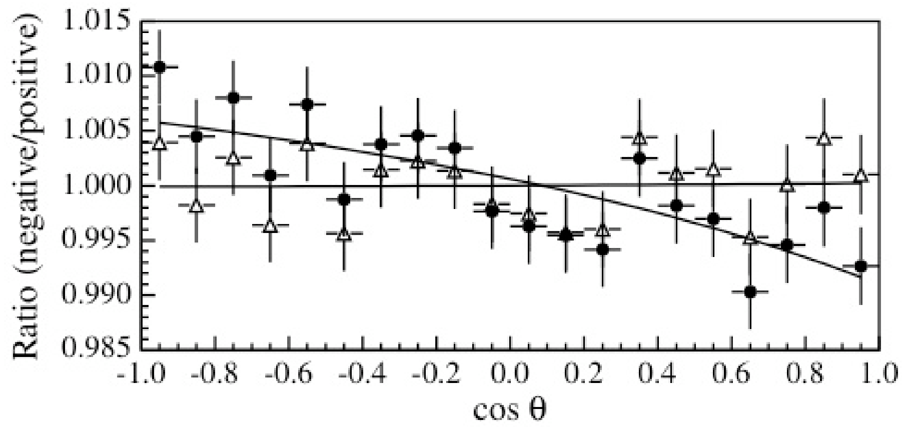

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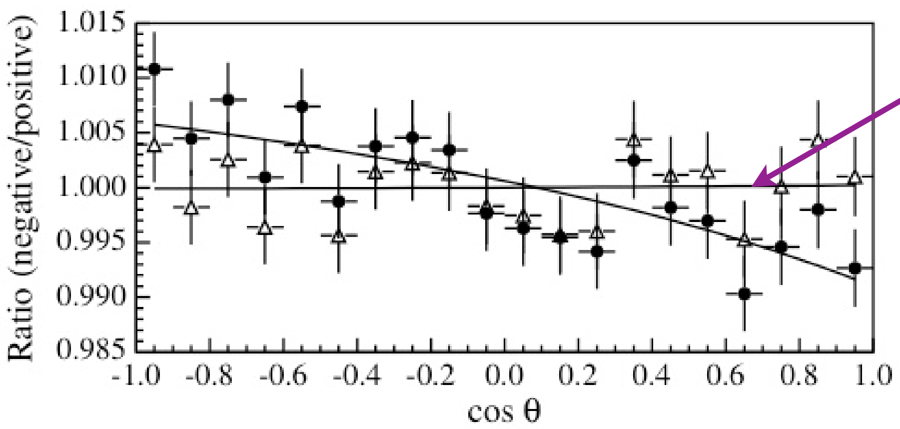

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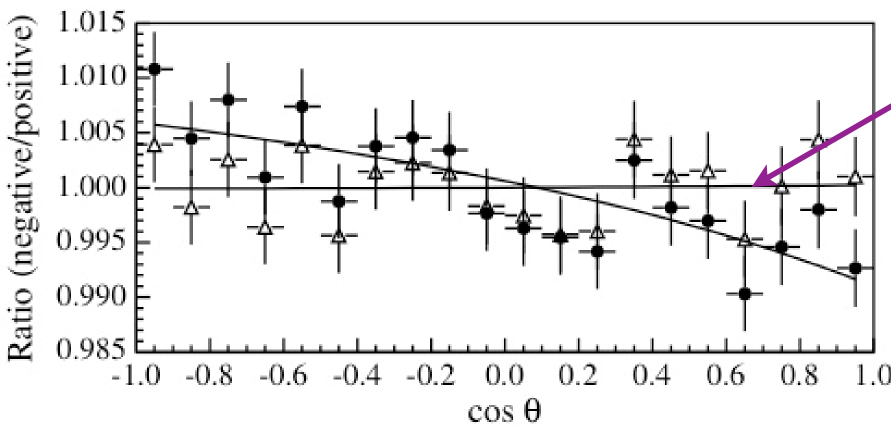

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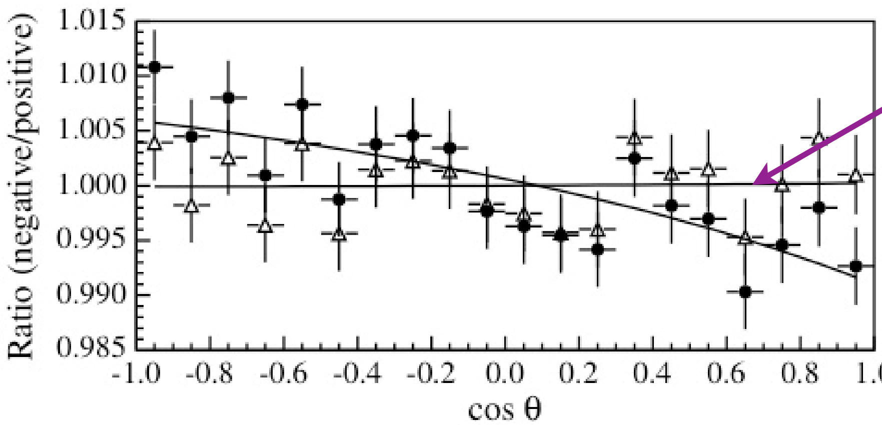

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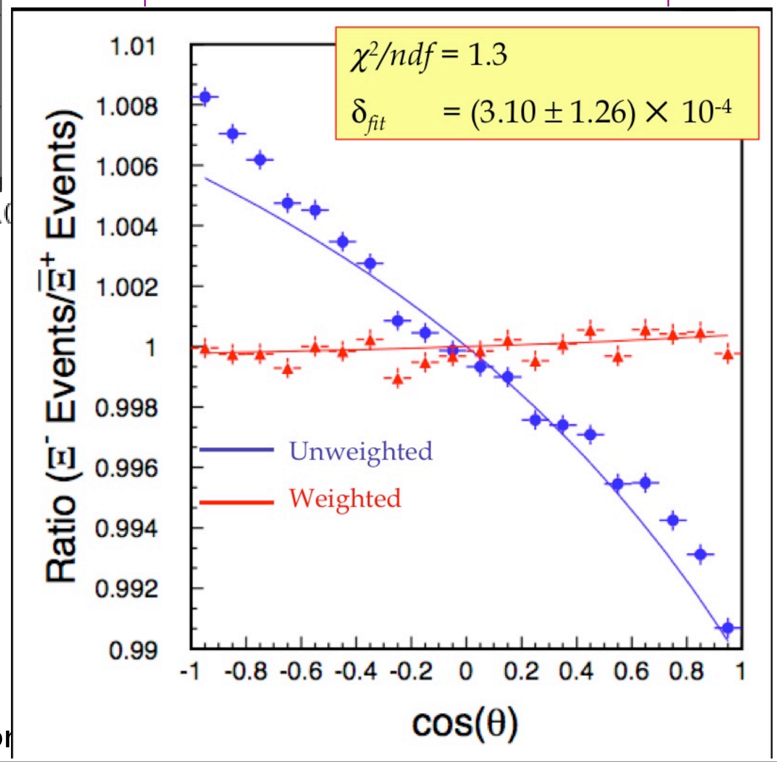

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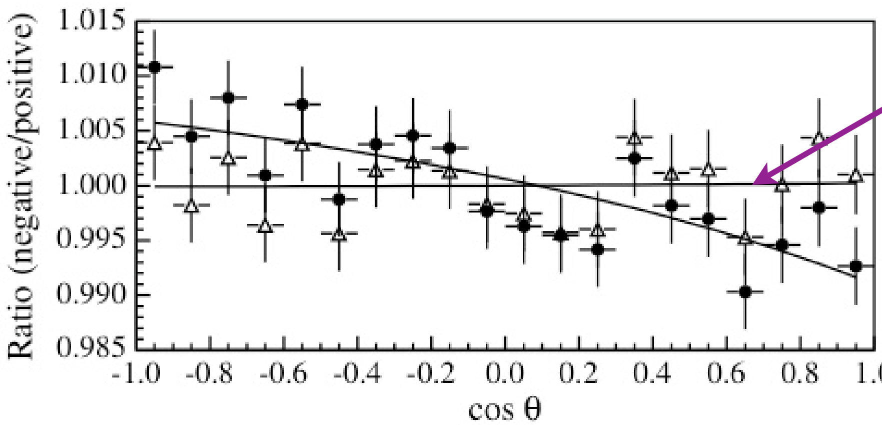

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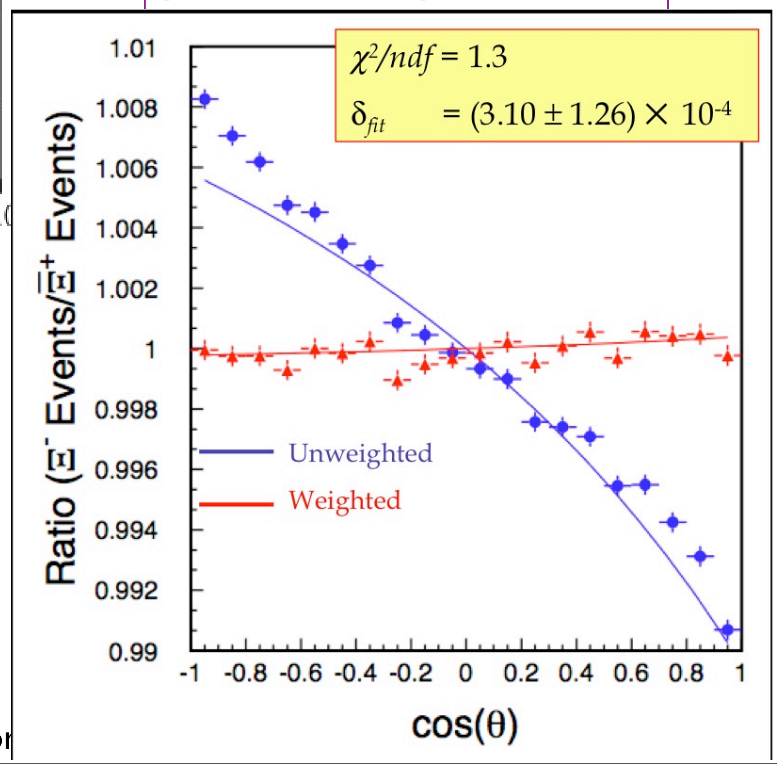

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$$A_{\Xi\Lambda} = \frac{\alpha_{\Xi}\alpha_{\Lambda} - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}{\alpha_{\Xi}\alpha_{\Lambda} + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}}$$

$$= [-6.0 \pm 2.1(stat) \pm 2.1(syst)] \times 10^{-4}$$

What Next?

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- CERN fixed-target not as good (energy, duty factor)
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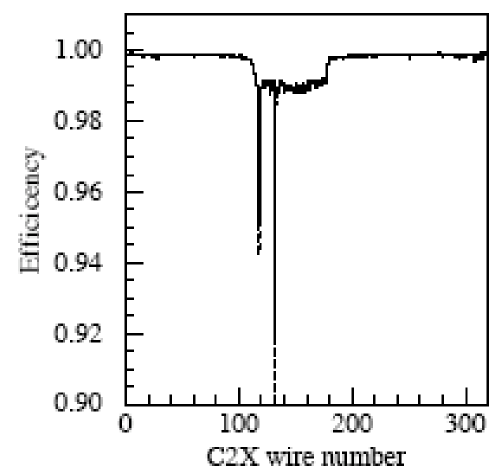

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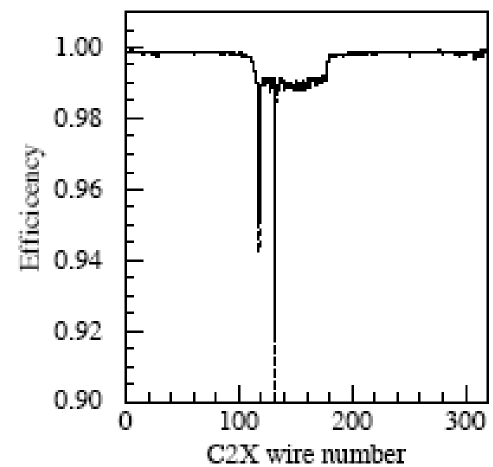

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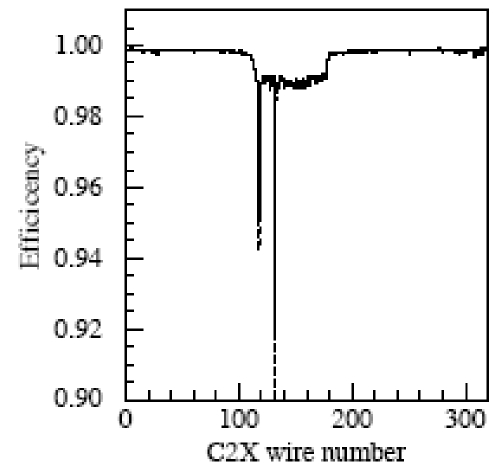

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➡ What else is there?

Low-Energy Antiprotons!

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Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 $\pm$ 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 $\pm$ 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	**0.006 $\pm$ 0.015**	[P.D. Barnes et al., NP B 56A (1997) 46]

Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 $\pm$ 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary]

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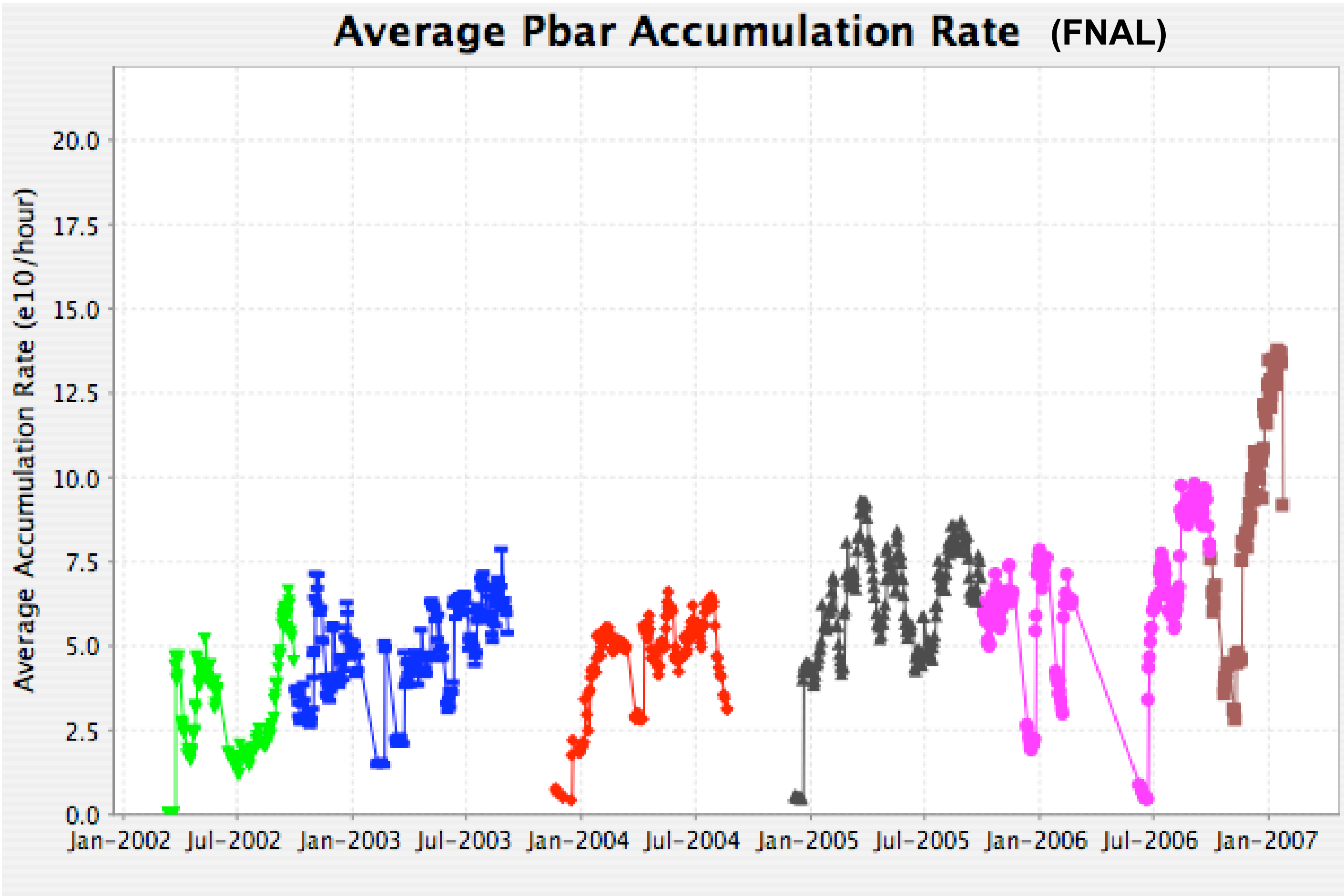

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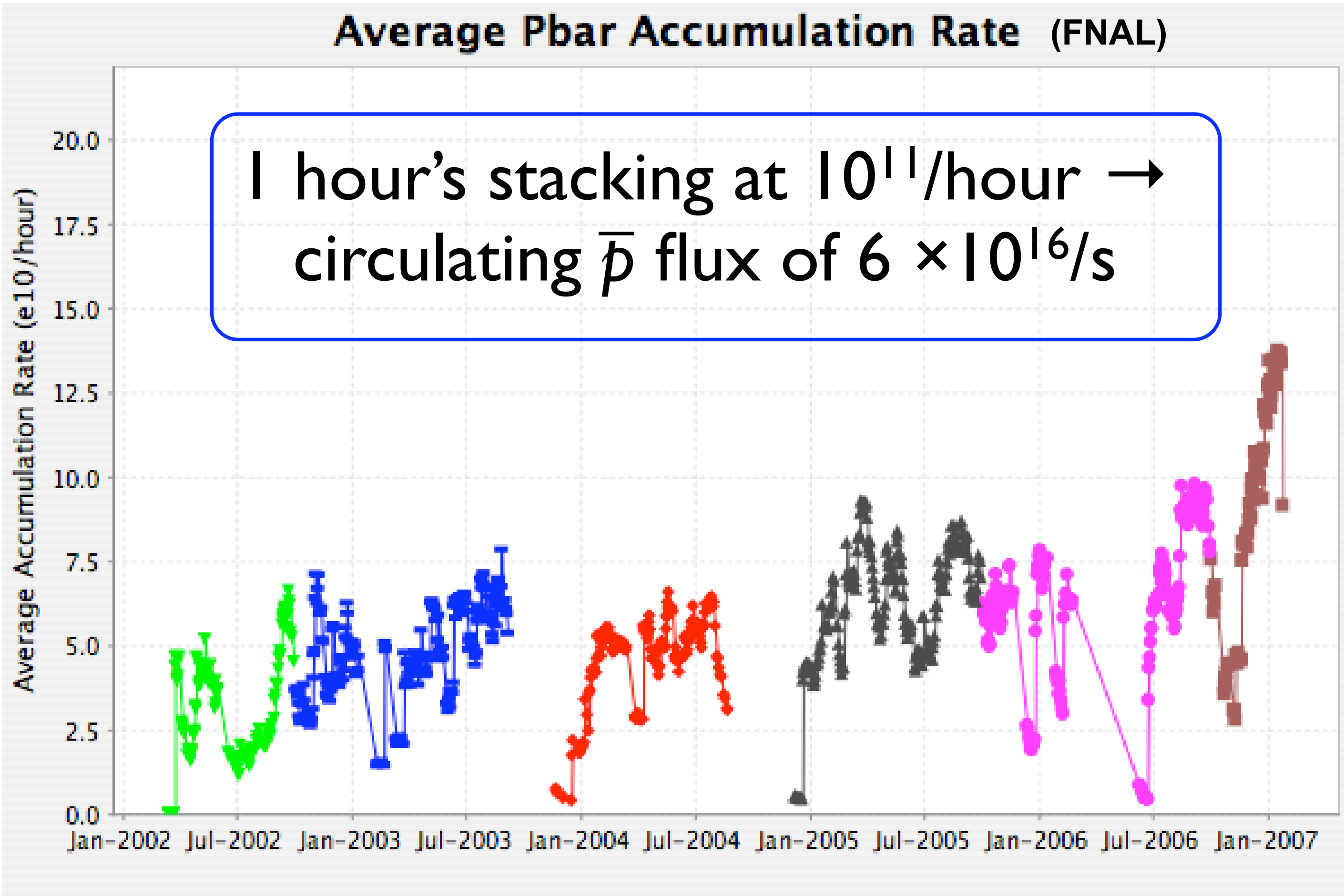

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$\boxed{\chi_{c0}(1P)}$ $I^G(J^{PC}) = 0^+(0^{++})$

$\chi_{c0}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3414.76$\pm$ 0.35 OUR AVERAGE		Error includes scale factor of 1.2.			
3414.21$\pm$ 0.39$\pm$0.27		ABLIKIM	05G	BES2	$\psi(2S) \to \gamma\chi_{c0}$
3414.7 $^{+0.7}_{-0.6}$ $\pm$0.2		[1] ANDREOTTI	03	E835	$\overline{p}p \to \chi_{c0} \to \pi^0\pi^0$
3415.5 $\pm$ 0.4 $\pm$0.4	392	[2] BAGNASCO	02	E835	$\overline{p}p \to \chi_{c0} \to J/\psi\gamma$
3417.4 $^{+1.8}_{-1.9}$ $\pm$0.2		[1] AMBROGIANI	99B	E835	$\overline{p}p \to e^+e^-\gamma$
3414.1 $\pm$ 0.6 $\pm$0.8		BAI	99B	BES	$\psi(2S) \to \gamma X$
3417.8 $\pm$ 0.4 $\pm$4		[1] GAISER	86	CBAL	$\psi(2S) \to \gamma X$

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$\boxed{\chi_{c0}(1P)}$ $\quad I^G(J^{PC}) = 0^+(0^{++})$

$\boxed{\chi_{c2}(1P)}$ $\quad I^G(J^{PC}) = 0^+(2^{++})$

See the Review on "$\psi(2S)$ and χ_c branching ratios" before the $\chi_{c0}(1P)$ Listings.

$\chi_{c2}(1P)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3556.20 ± 0.09 OUR AVERAGE					
3555.70 ± 0.59 ±0.39		ABLIKIM	05G	BES2	$\psi(2S) \to \gamma\chi_{c2}$
3556.173± 0.123±0.020		ANDREOTTI	05A	E835	$p\overline{p} \to e^+e^-\gamma$
3559.9 ± 2.9		EISENSTEIN	01	CLE2	$e^+e^- \to e^+e^-\chi_{c2}$
3556.4 ± 0.7		BAI	99B	BES	$\psi(2S) \to \gamma X$
3556.22 ± 0.131±0.020	585	[1] ARMSTRONG	92	E760	$\overline{p}p \to e^+e^-\gamma$

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  - Thanks to superb precision of antiproton beam energy and momentum spread, E760/835 @ Fermilab Antiproton Accumulator made very precise measurements of charmonium parameters, e.g.:
    - best measurements of various η_c, χ_c, h_c masses, widths, branching ratios,...
    - interference of continuum & resonance signals
- FAIR to build similar facility at Darmstadt, done ≈2016

Low-Energy Antiprotons!

- Fermilab Antiproton Source is world's highest-energy and most intense

Table I: Antiproton Intensities at Existing and Future Facilities

Facility	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Clock Hours /Yr	$\overline{\mathrm{p}}$/Yr (10^{13})
CERN AD			3800	0.4
FNAL (Accumulator)	20	15%	5550	17
FNAL (New Ring)	20	90%	5550	100
FAIR ($\geq$2015)	3.5	90%	2780	9

...even after FAIR turns on

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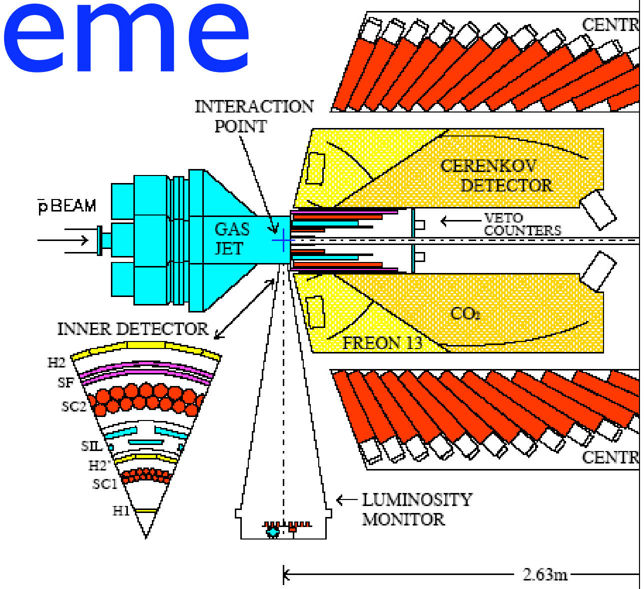

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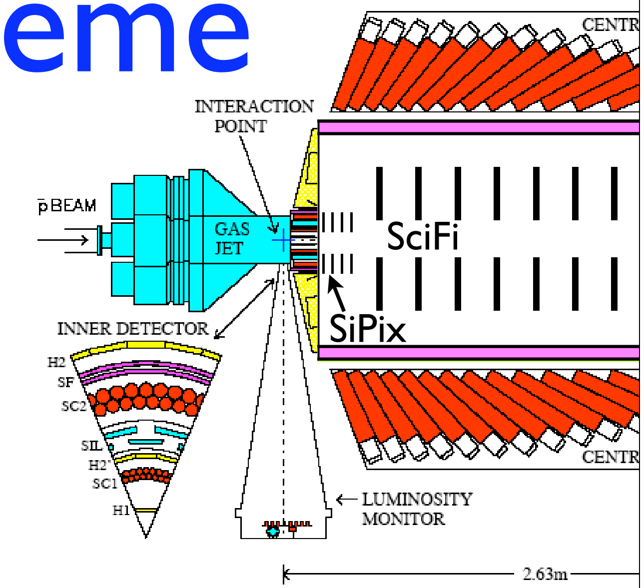

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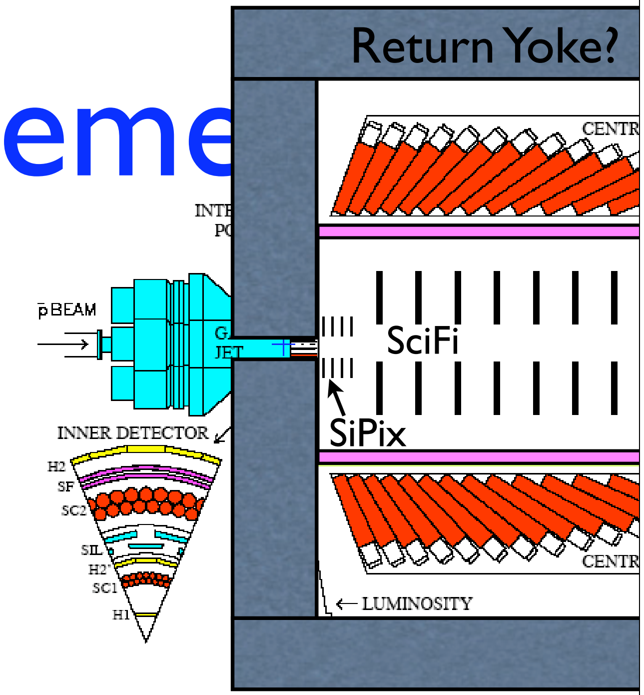

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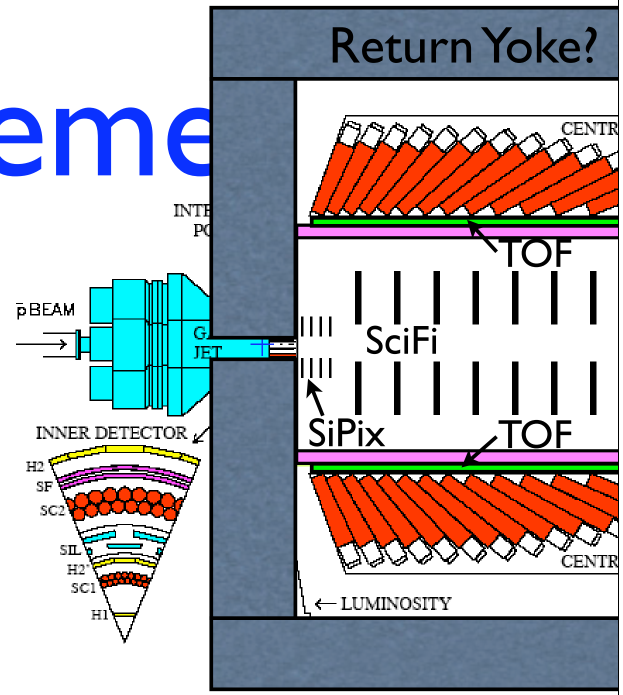

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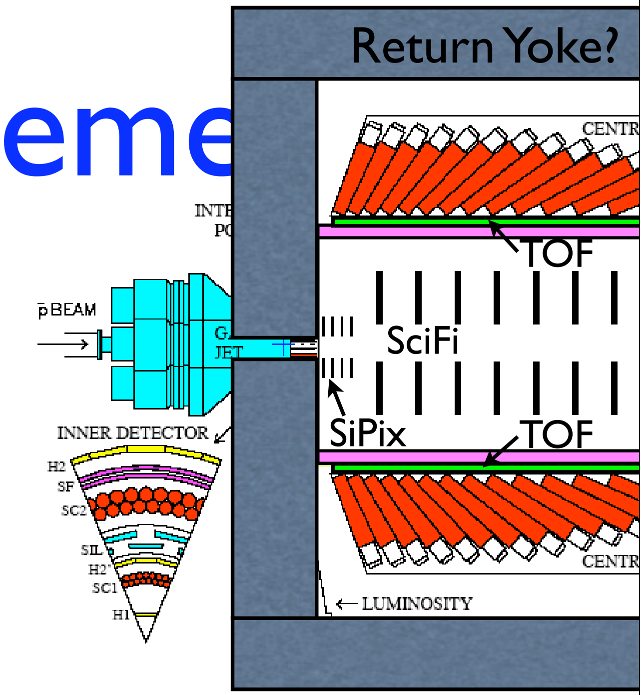

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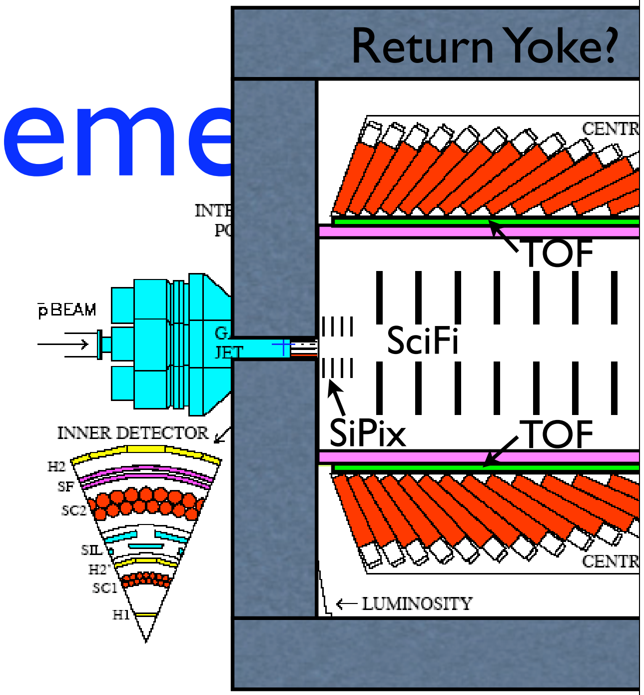

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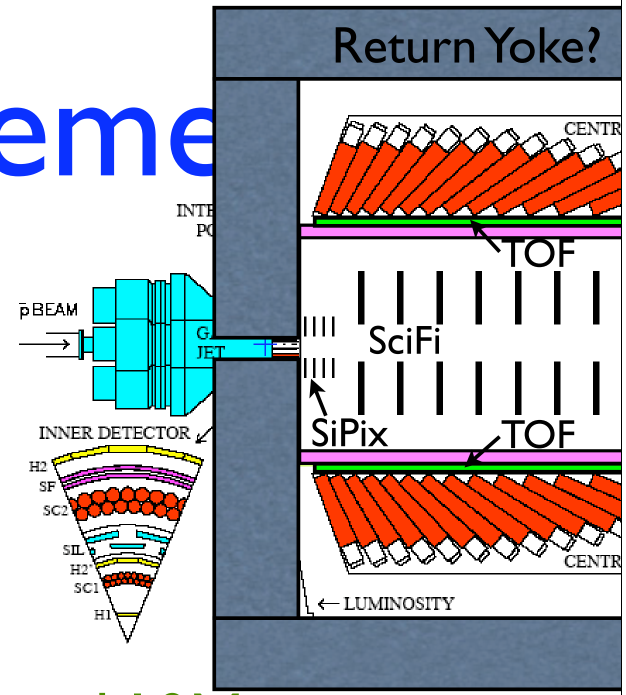

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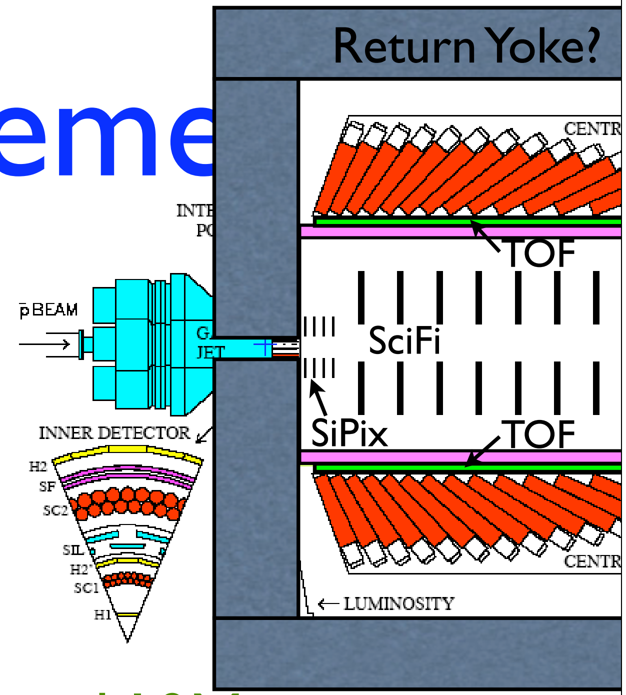

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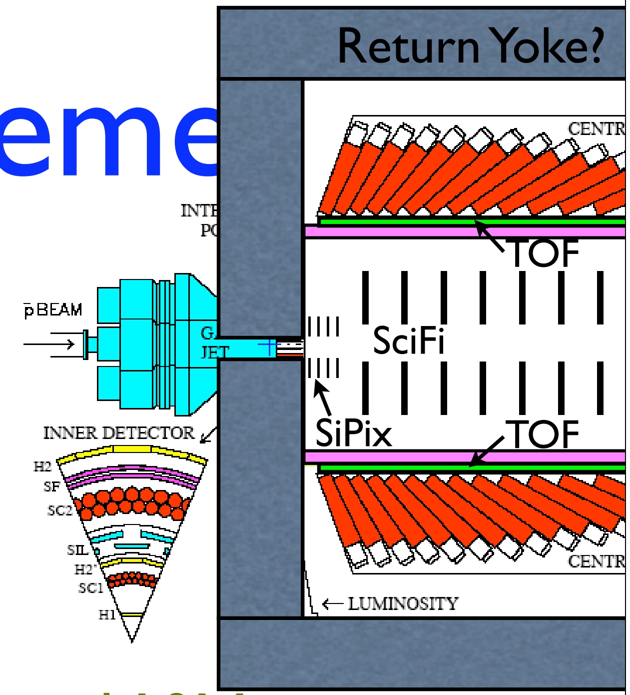

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  ➡ ~10^8 $\Omega^- \overline{\Omega}^+$/yr

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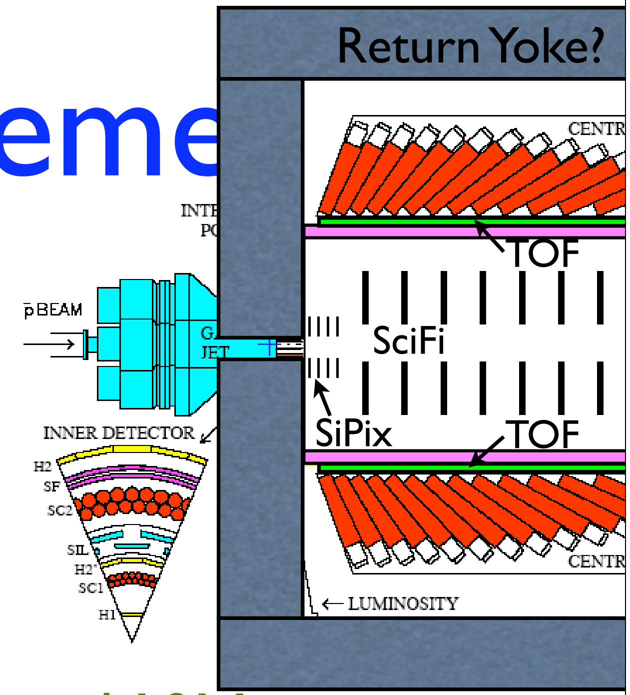

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<$10M

➡ $\sim 10^8\ \Omega^- \overline{\Omega}^+$/yr + $\sim 10^{12}$ inclusive hyperon events!

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Predicted $\Delta\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

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- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$

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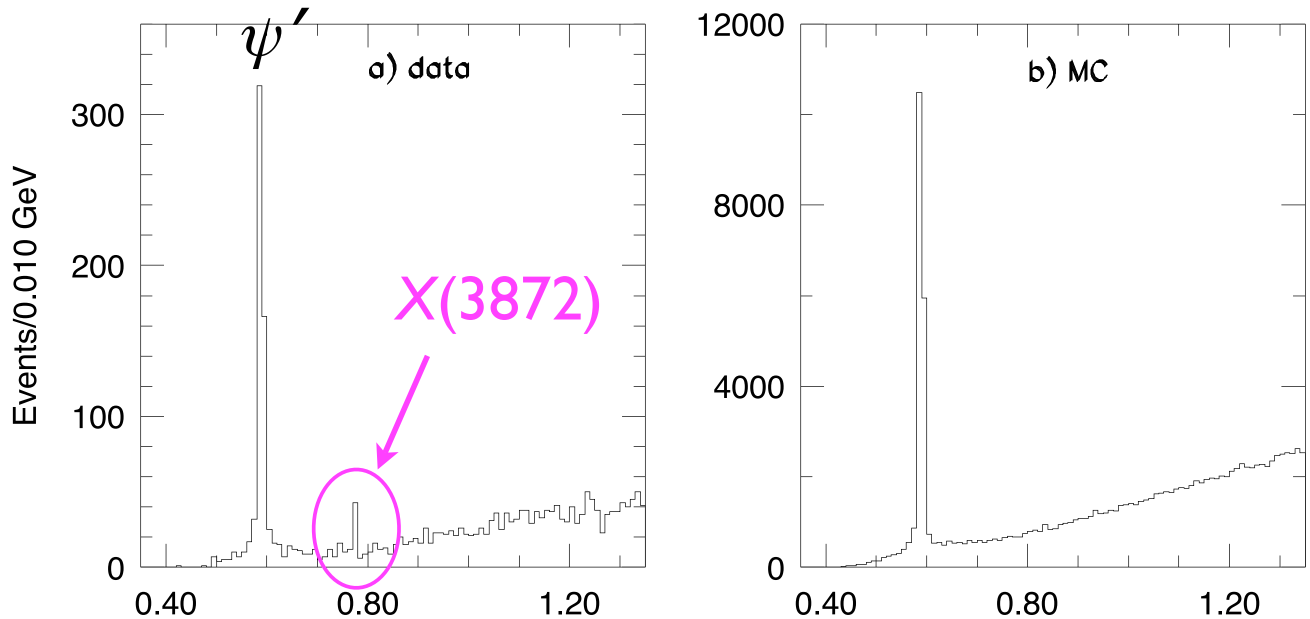
- Much interest lately in new states observed in charmonium region: *X*(3872), *X*(3940), *Y*(3940), *Y*(4260), and *Z*(3930)
- *X*(3872) of particular interest b/c may be the first hadron-antihadron ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

What Else Can This Do?

- Belle, Aug. 2003: $B^{\pm} \longrightarrow X + K^{\pm}, X \longrightarrow J/\psi\, \pi^{+}\pi^{-}$



- Since confirmed by CDF, D0, & BaBar
- Not consistent with being charmonium state
- Very near $D^0\,\overline{D}^{*0}$ threshold (Δmc^2 = −0.35±0.69 MeV)

XYZ hadronic transitions

- Many new states : ?

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	$3871.2\pm0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	$3929\pm5\pm2 + i(29\pm10\pm2)$	2^{++}	$D^0 D^0$, $D^+ D^-$	$\gamma\gamma$
Y(3940)	Belle BaBar	$3943\pm11\pm13 + i(87\pm22\pm26)$ $3914.3^{+3.8}_{-3.4} \pm1.6 + i(33^{+12}_{-8} \pm0.60)$	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6}\pm6 + i(37^{+26}_{-15}\pm8)$	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008\pm40^{+72}_{-28} + i(226\pm44^{+87}_{-79})$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20}\pm15 + i(139^{+111}_{-61}\pm21)$	J^{P+}	D^*D^*	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259\pm8^{+8}_{-6} + i(88\pm23^{+6}_{-4})$ $4284^{+17}_{-16} \pm4 + i(73^{+39}_{-25}\pm5)$ $4247\pm12^{+17}_{-32} + i(108\pm19\pm10)$	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324\pm24 + i(172\pm33)$ $4361\pm9\pm9 + i(74\pm15\pm10)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	$4433\pm4\pm1 + i(44^{+17}_{-13}{}^{+30}_{-11})$	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	$4664\pm11\pm5 + i(48\pm15\pm3)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

What Else Can This Do?

- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$
- $X(3872)$ of particular interest b/c may be the first hadron-antihadron ($D^0 \overline{D}^{*0}$ + c.c.) molecule

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➡ need very precise mass & width measurement to confirm or refute

➡ $\overline{p}p \to X(3872)$ formation *ideal* for this

What Else Can This Do?

Also,...

- Study other *X*, *Y*, *Z* states
- Worthwhile measurements that E835 could have made but didn't...

  (lack of beam time for precision scans when one didn't know exactly where to look)

  - h_c mass & width, χ_c radiative-decay angular distributions, η_c' full and radiative widths,...
- ...improved limits on $\bar{p}$ lifetime and branching ratios (APEX),...

What Else Can This Do?

Charm!

Charm!

PHYSICAL REVIEW D **77,** 034019 (2008)

Estimate of the partial width for $X(3872)$ into $p\bar{p}$

Eric Braaten

Physics Department, Ohio State University, Columbus, Ohio 43210, USA

(Received 13 November 2007; published 25 February 2008)

We present an estimate of the partial width of $X(3872)$ into $p\bar{p}$ under the assumption that it is a weakly bound hadronic molecule whose constituents are a superposition of the charm mesons $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$. The $p\bar{p}$ partial width of X is therefore related to the cross section for $p\bar{p} \to D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \to K^{*-}K^+$. It is extrapolated to the $D^{*0}\bar{D}^0$ threshold by taking into account the threshold resonance in the 1^{++} channel. The resulting prediction for the $p\bar{p}$ partial width of $X(3872)$ is proportional to the square root of its binding energy. For the current central value of the binding energy, the estimated partial width into $p\bar{p}$ is comparable to that of the P-wave charmonium state χ_{c1}.

- Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming $D^*\bar{D}$ molecule

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  - extrapolates from $K^*\bar{K}$ data

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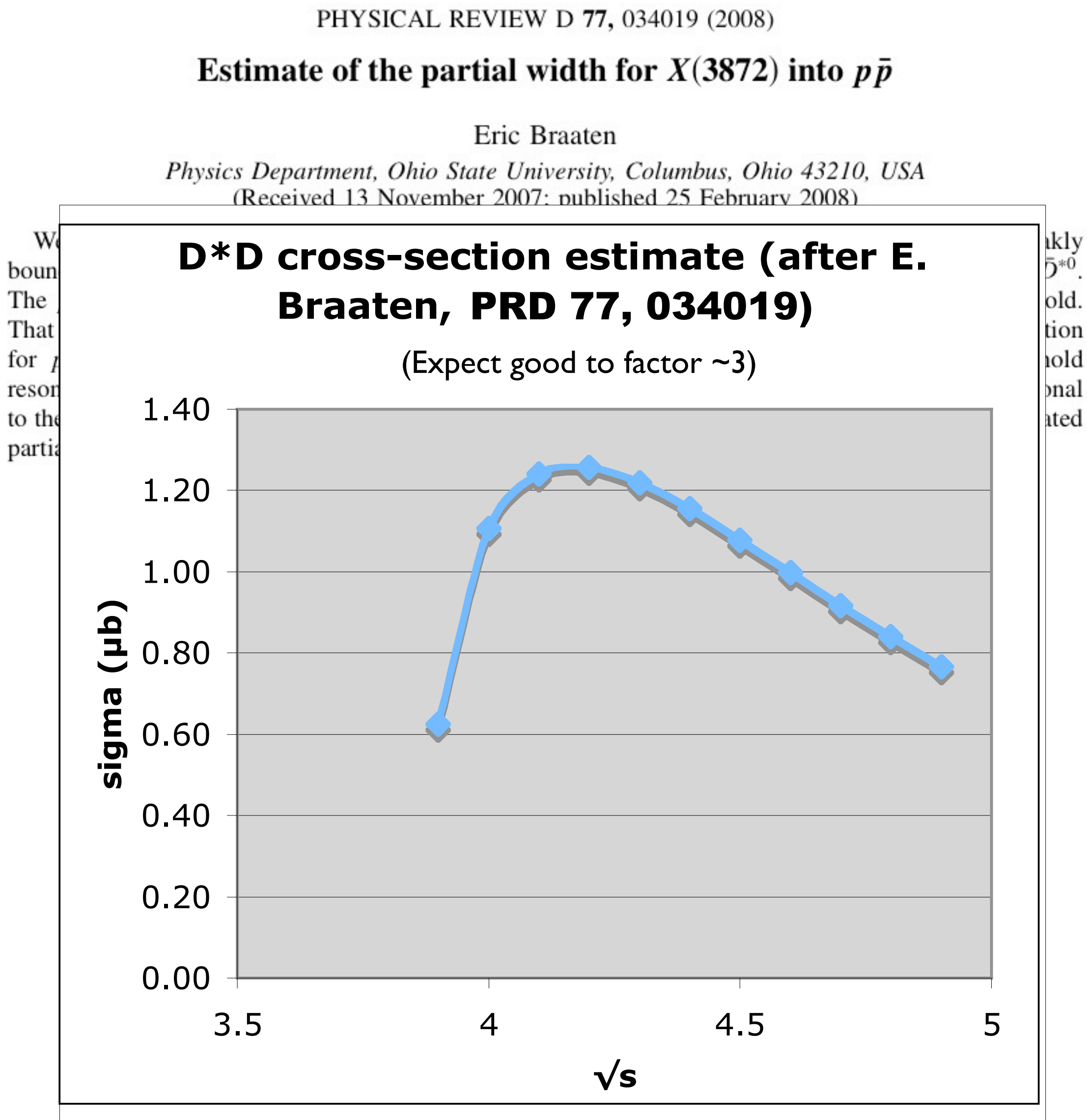
  - extrapolates from $K^*\bar{K}$ data
- By-product is $D^*\bar{D}$ cross section

Charm!



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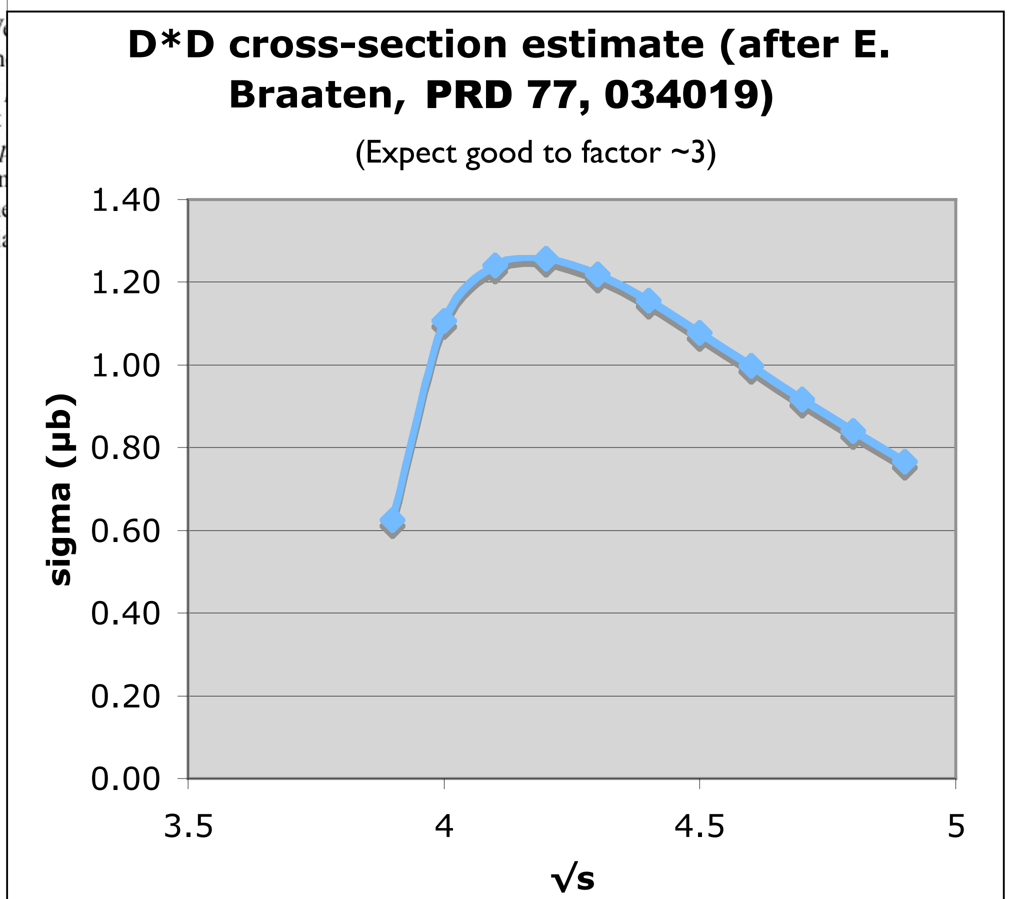

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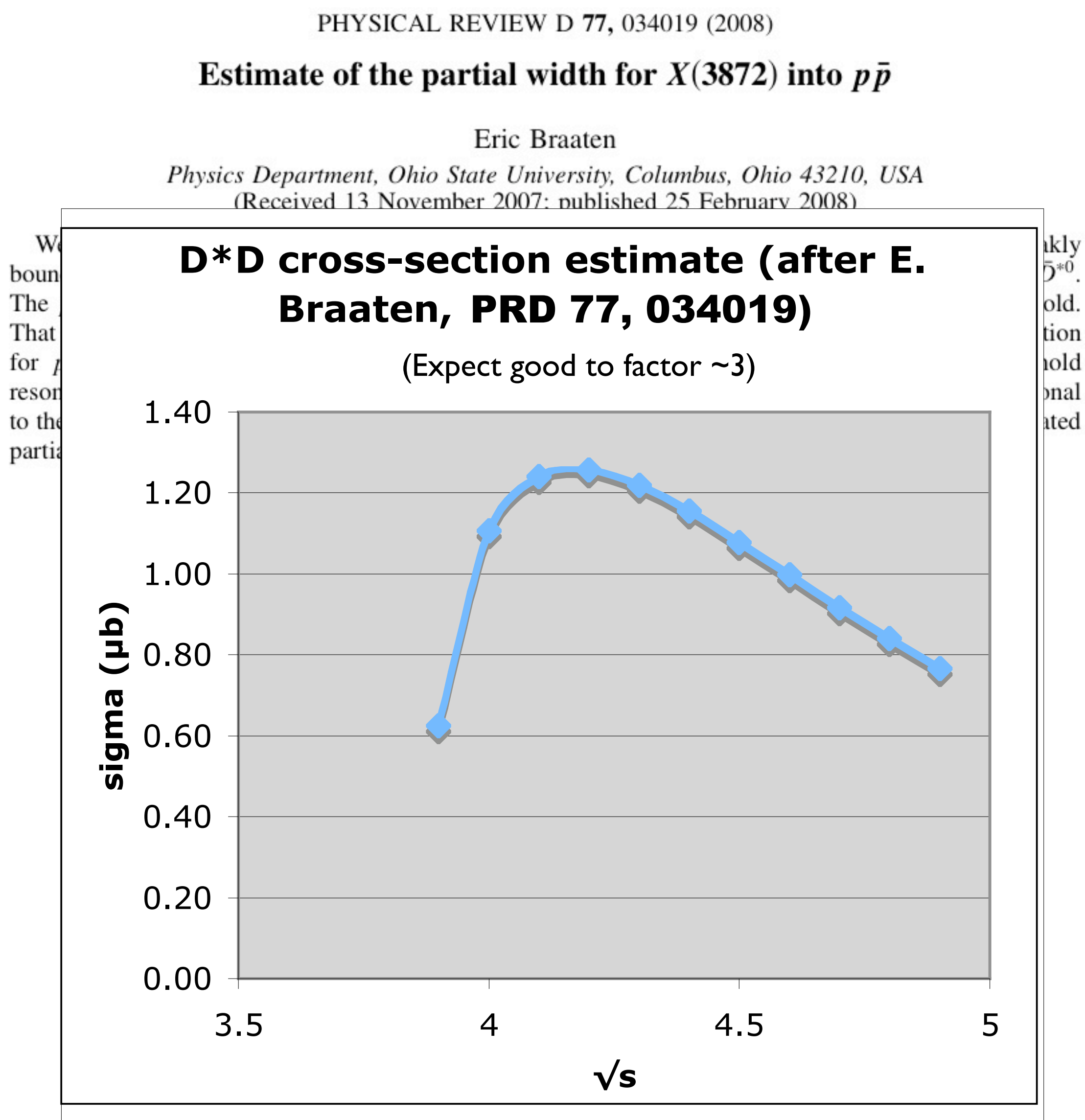

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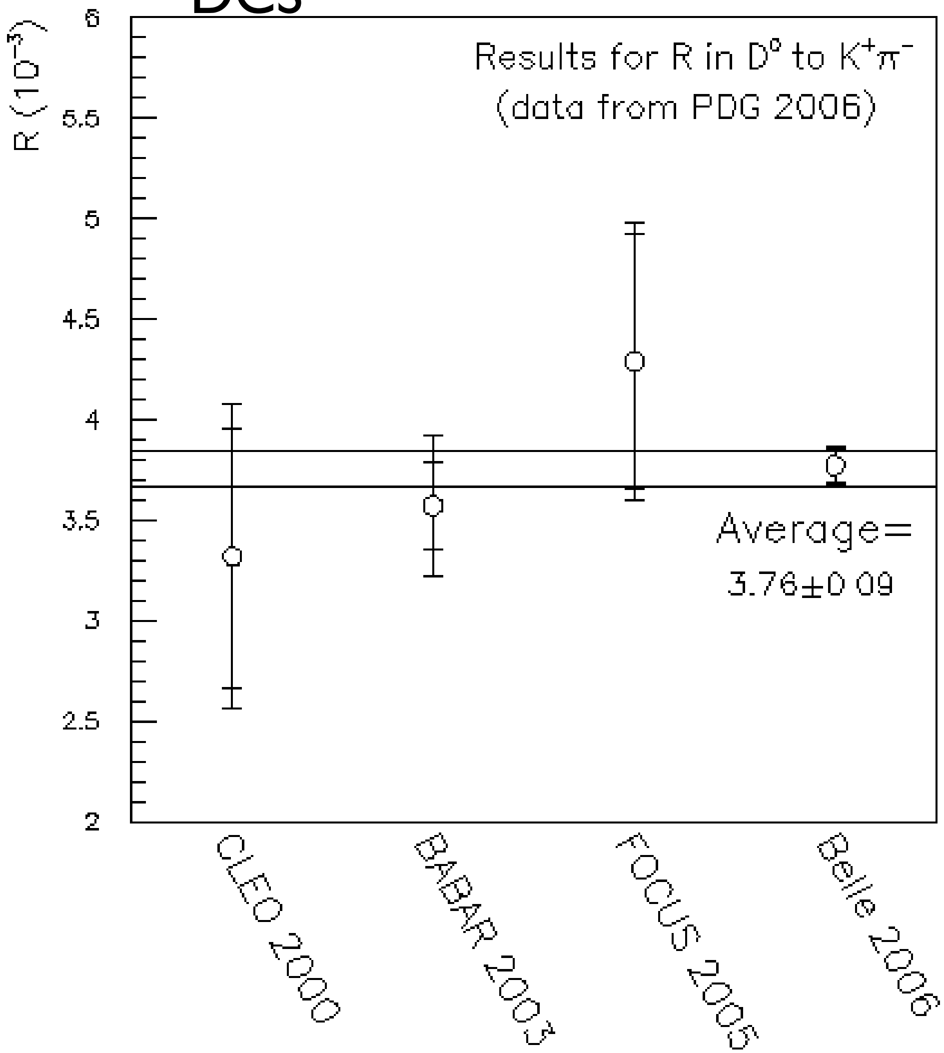
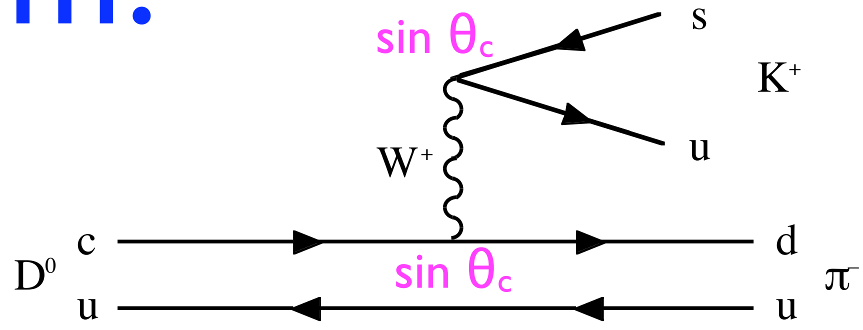
- Expect efficiency as at *B* factories

Charm!

- $D^0 \xrightarrow[\text{DCS}]{\text{mixing}} K^+\pi^-$; $R \equiv \Gamma_{DCS} / \Gamma_{CF}$





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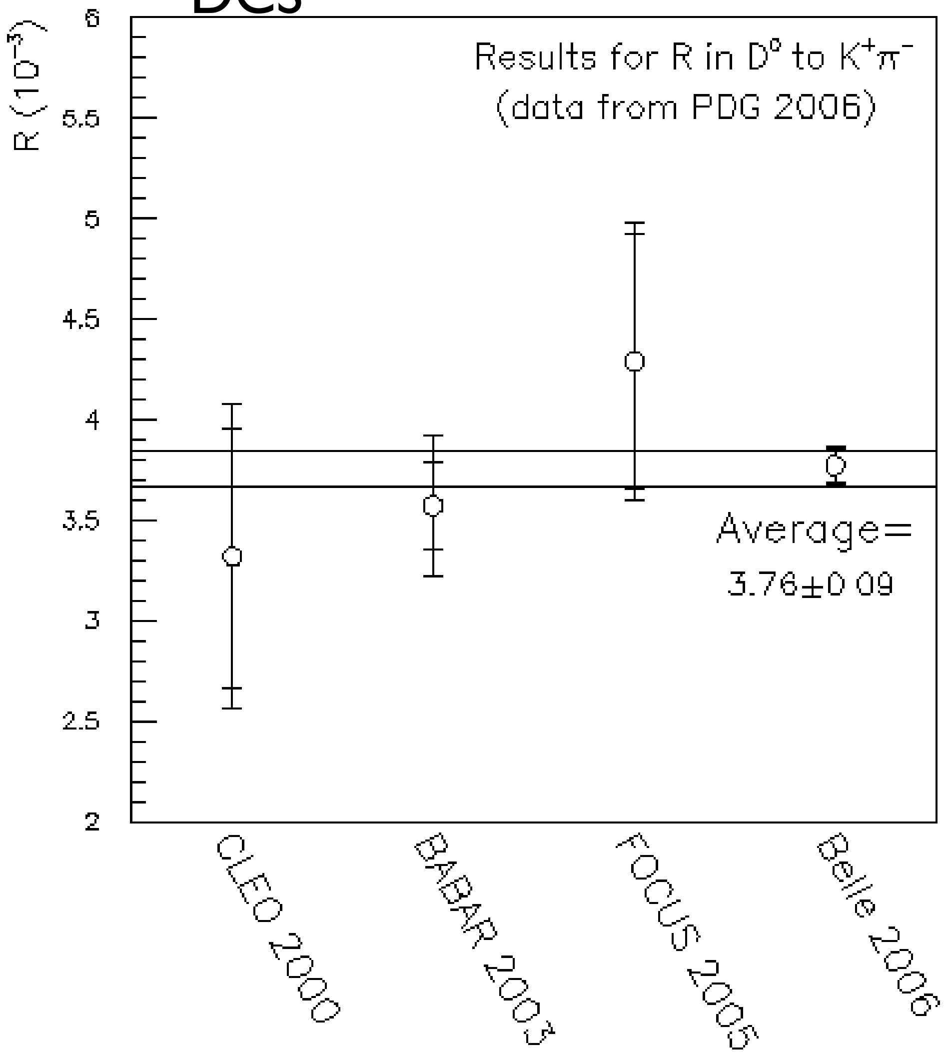

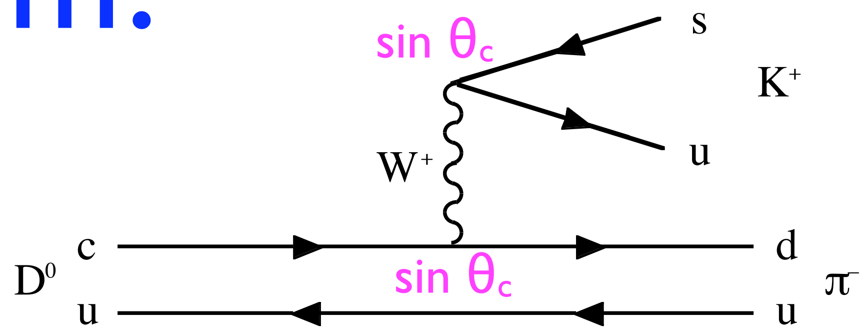

Interference with DCSD amplifies mixing signal:

$$\Gamma[D^0 \to K^+\pi^-] = e^{-\Gamma t}|A_{K^-\pi^+}|^2 \times$$
$$\left[R + \sqrt{R}R_m(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{R_m^2}{4}(y^2+x^2)(\Gamma t)^2\right]$$

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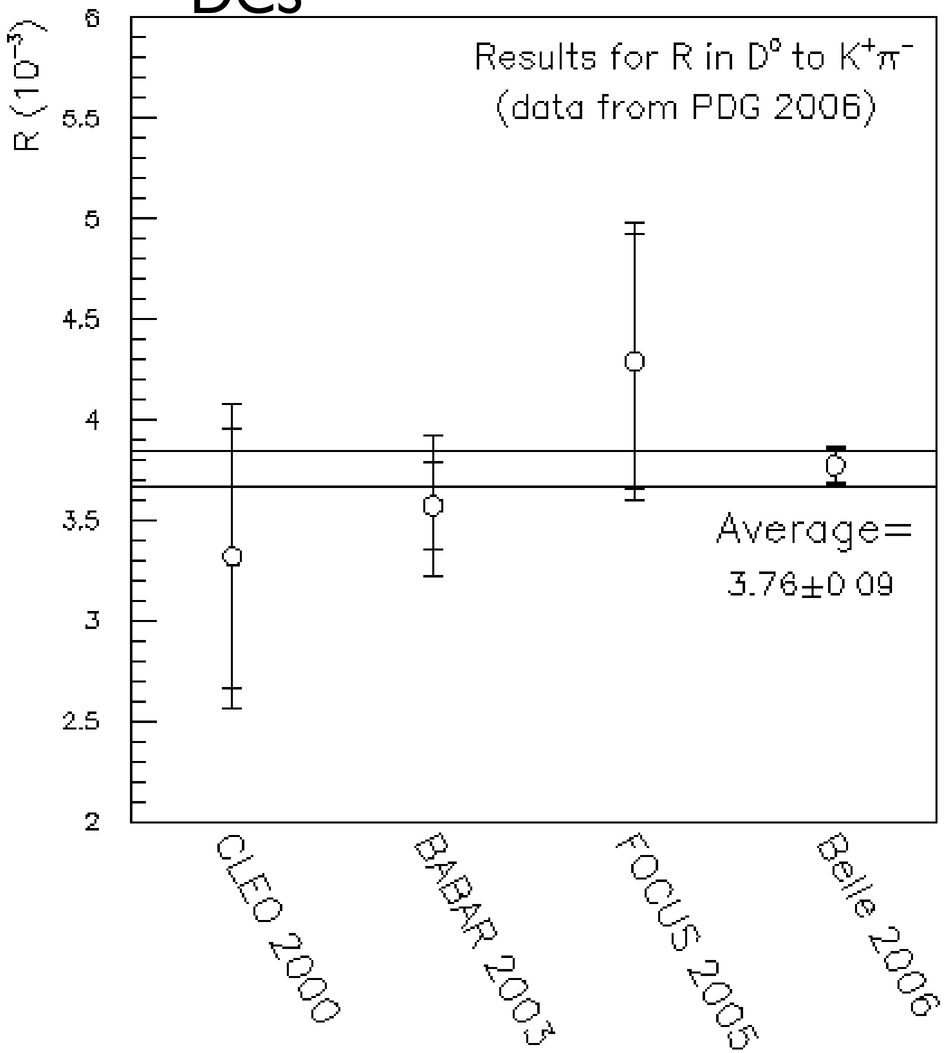

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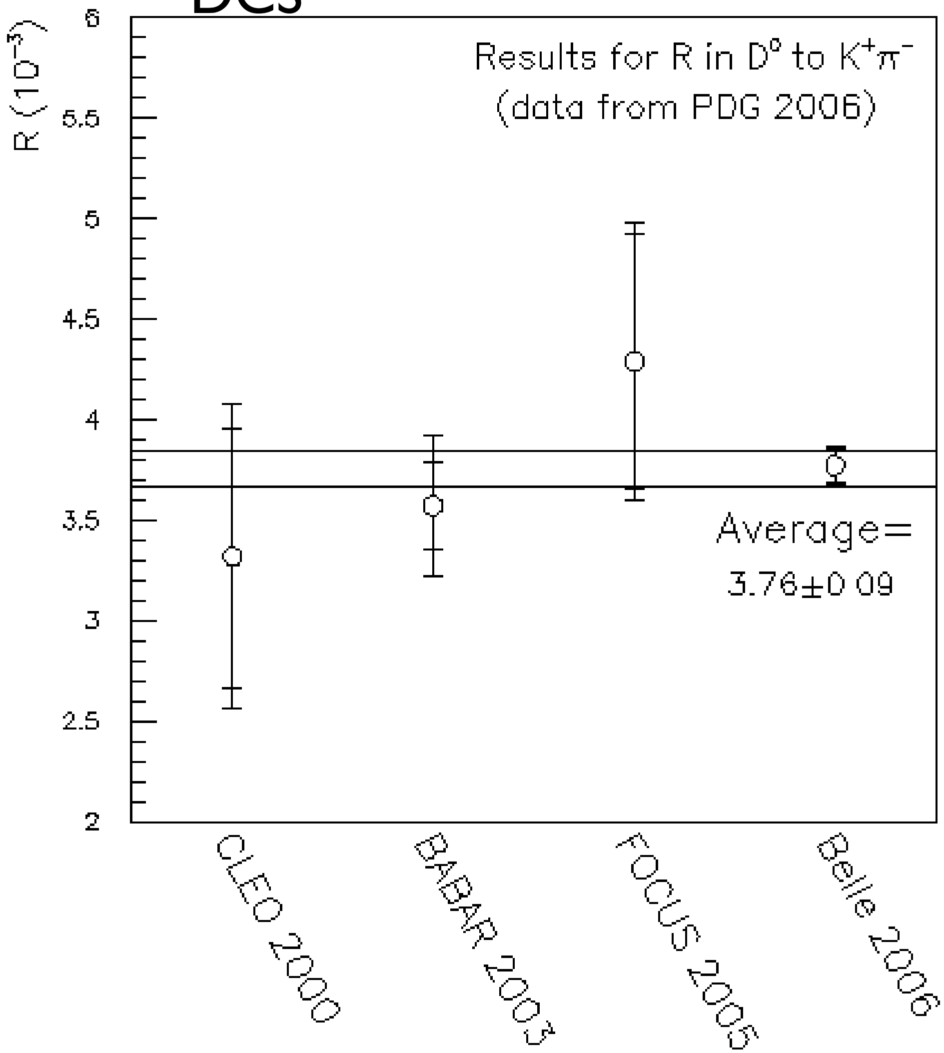

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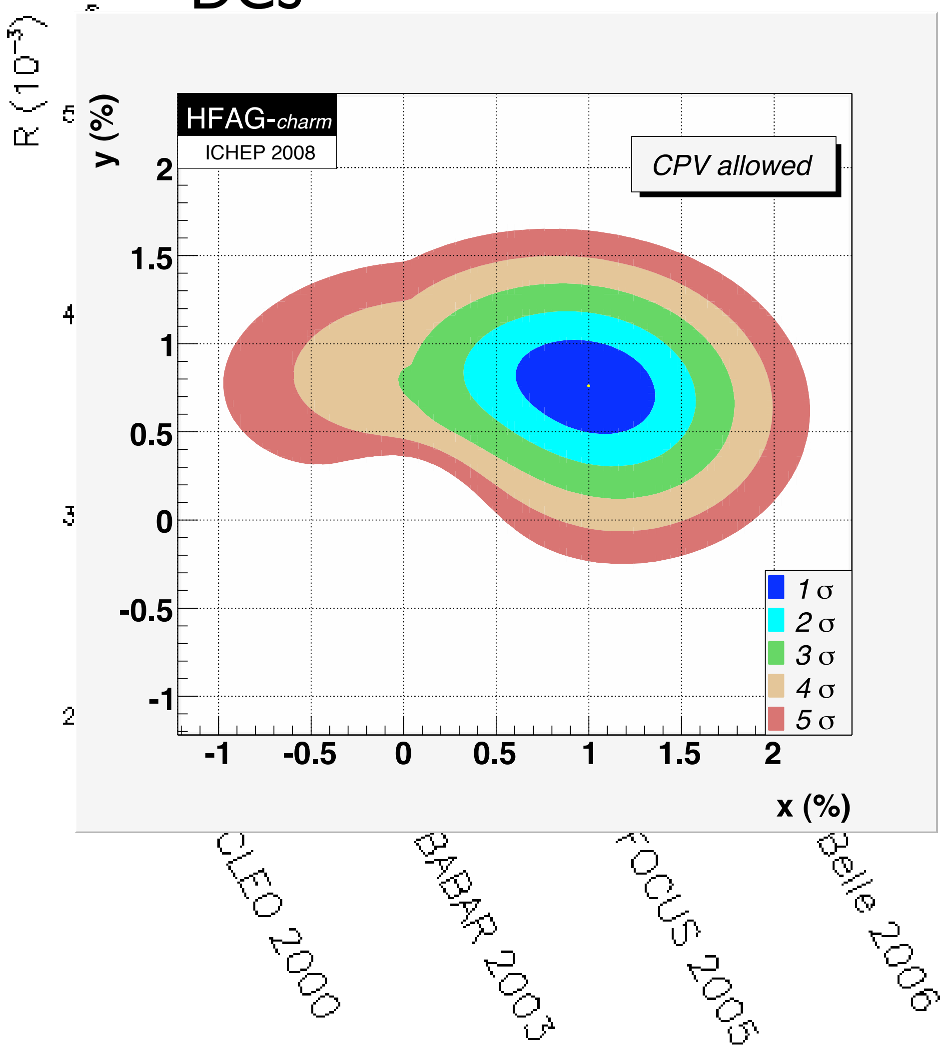

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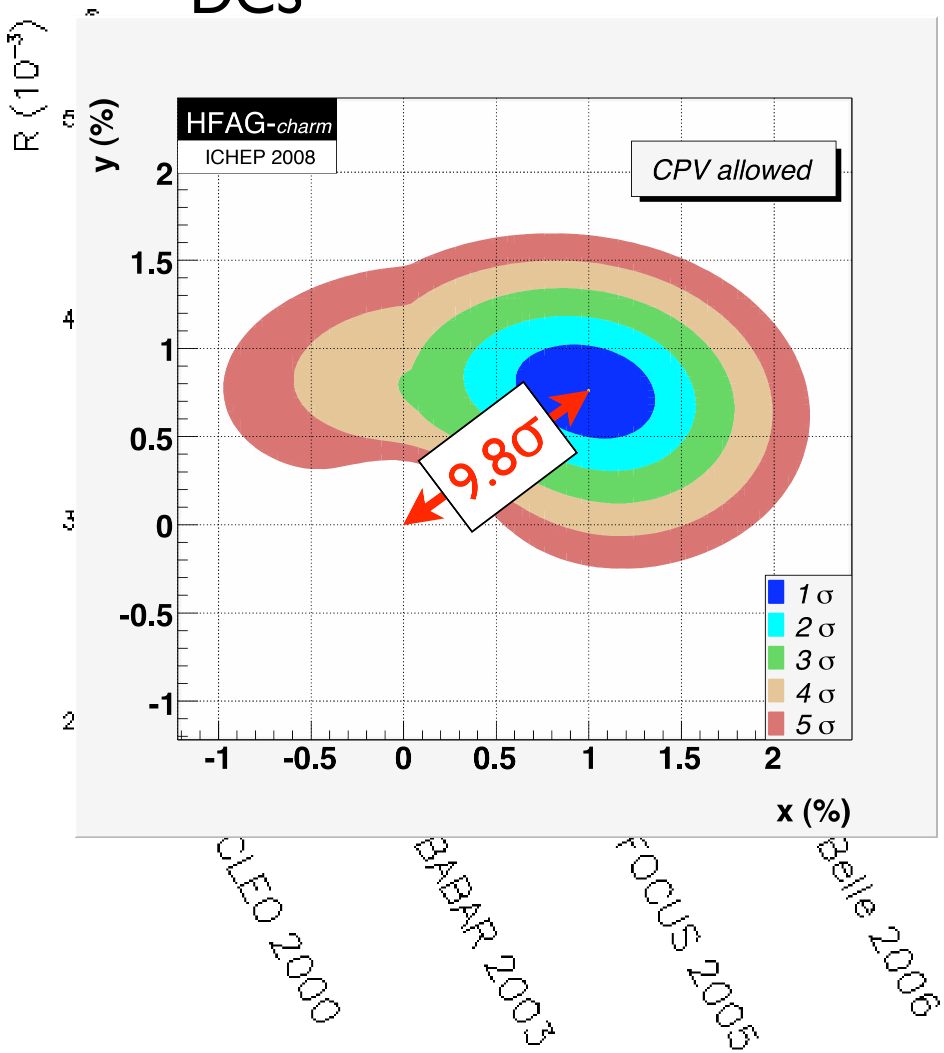

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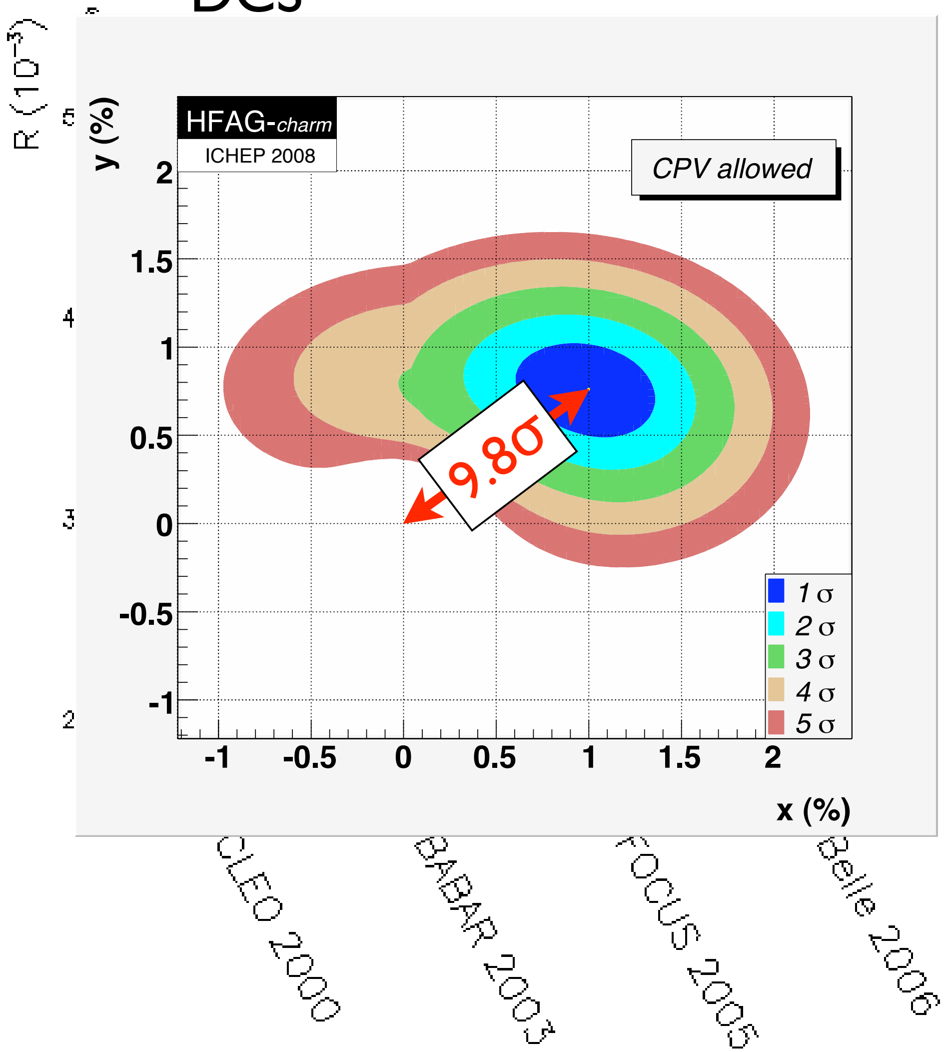

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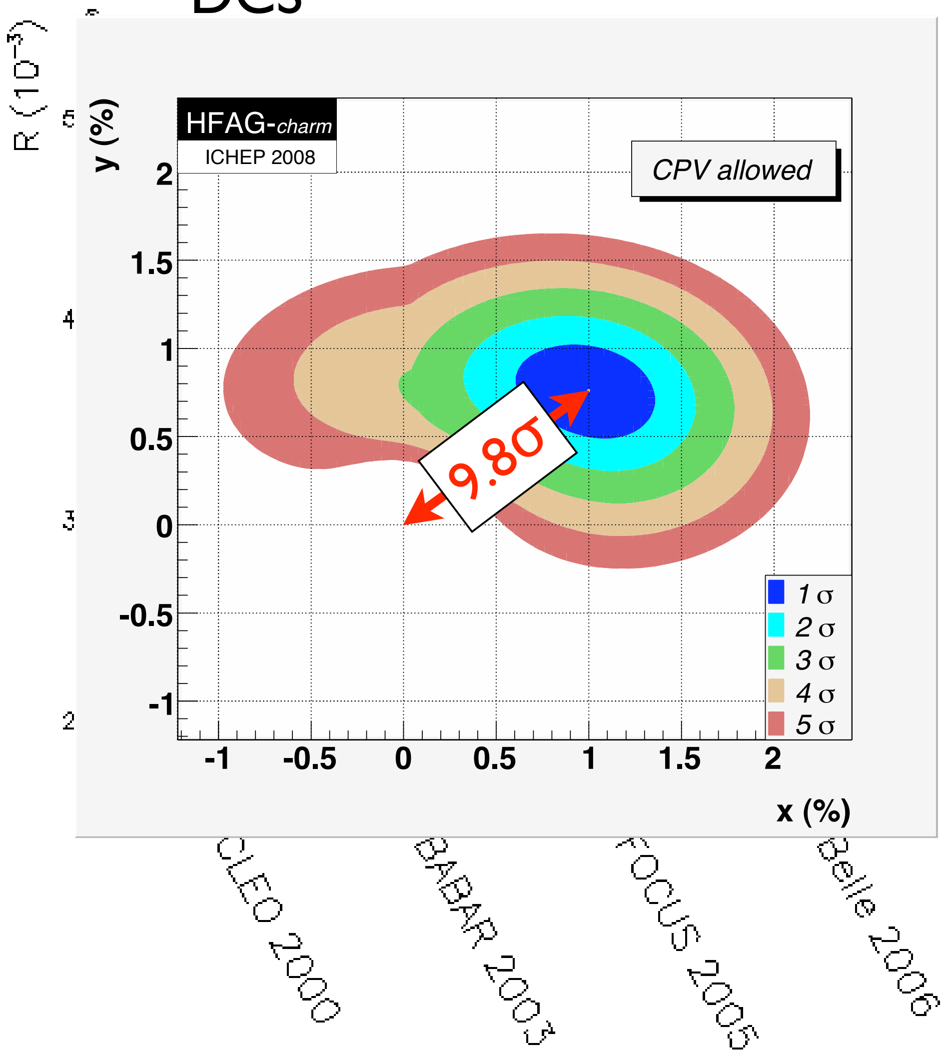

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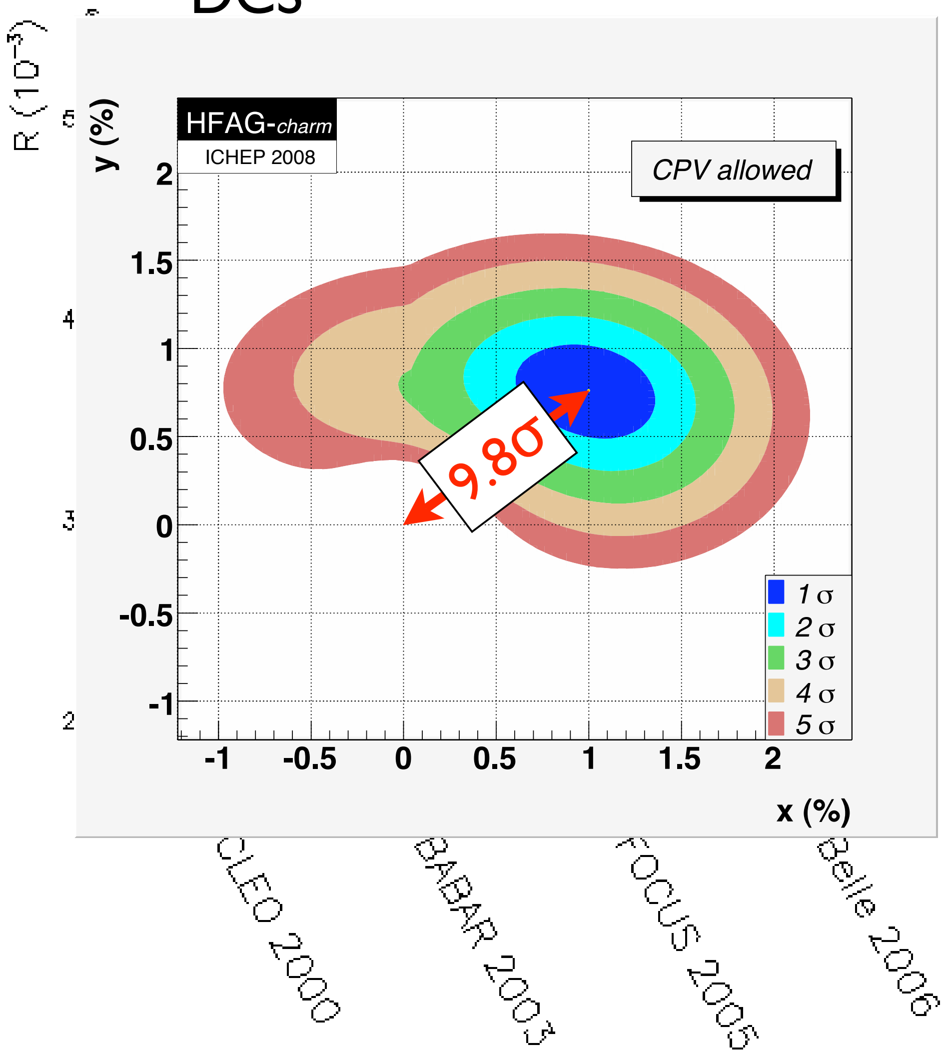

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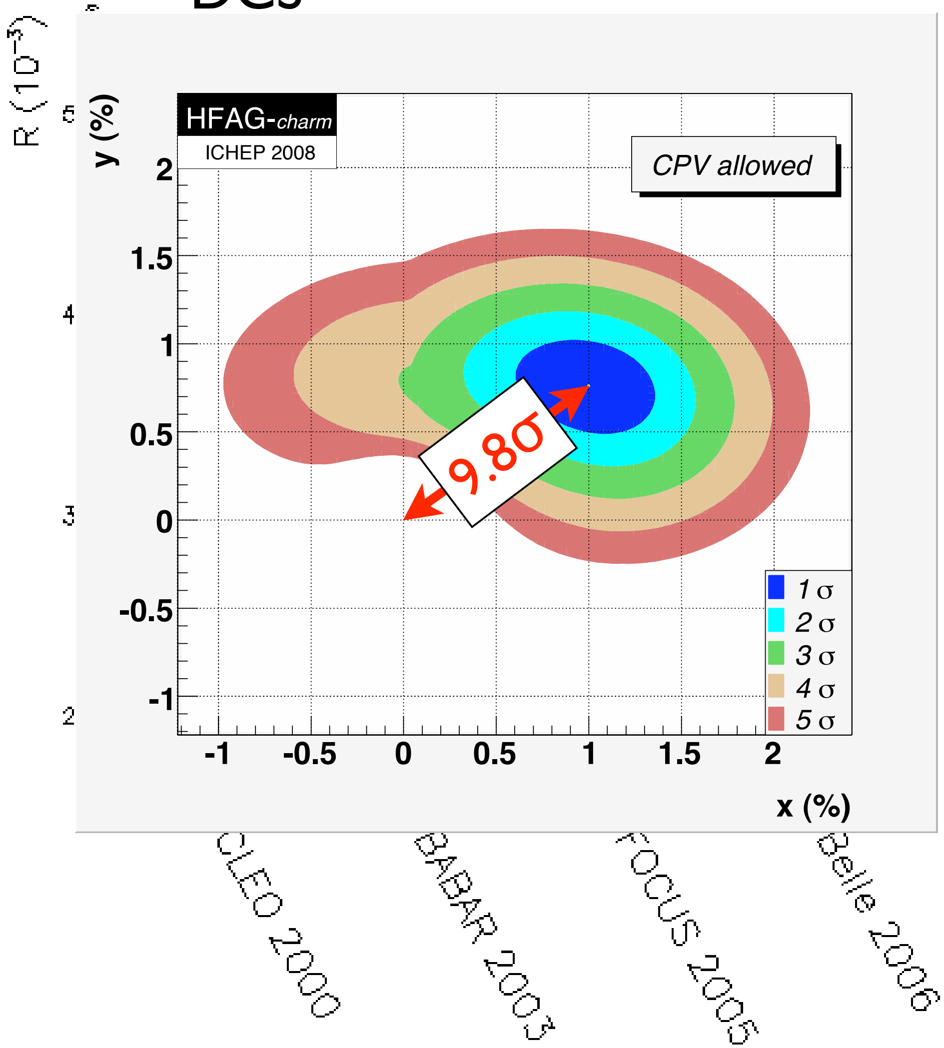

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- *B* factories have ~10^9 open-charm events
- $\overline{p}p$ can produce ~10^{10}/y

Charm!

- Ballpark sensitivity estimate using cross section based on Braaten $\overline{p}p \rightarrow D^{*0}\overline{D}^0$ formula and assuming $\sigma \propto A^{1.0}$:

Quantity	Value	Unit
Running time	2×10^7	s/y
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\text{cm}^{-2}\text{s}^{-1}$
Target A	27	
$A^{0.29}$	2.6	
$\sigma(\overline{p}p \rightarrow D^{*+}X)$	1.25	μb
# $D^{*\pm}$ produced	2.1×10^{10}	events/y
$\mathcal{B}(D^{*+} \rightarrow D^0\pi^+)$	0.677	
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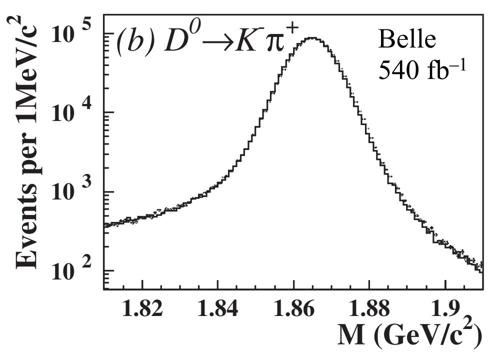

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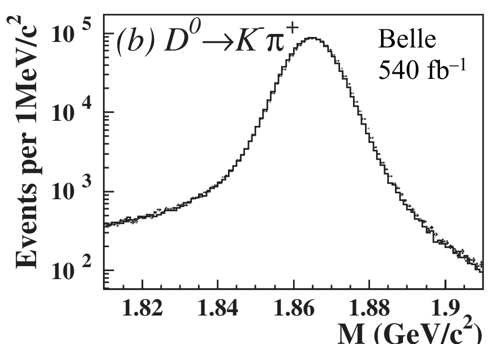

- LHC*b* will have comparable statistics but diff't systematics

Charm!

- Another possibility (E. Braaten): use the X(3872) as a pure source of $D^{*0}\overline{D}^0$ events
  - the $\overline{p}p$ equivalent of the $\Psi(3770)$!?
  - assuming current Antiproton Accumulator parameters ($\Delta p/p$) & Braaten estimate, produce ~10^8 events/year
  - comparable to BES-III statistics
  - could gain factor ~5 via AA e^- cooling?
- Proposed expt will establish feasibility & reach

...and **now**

for *something*

completely <u>different</u>!

Antihydrogen

Antihydrogen

- Long quest at LEAR, then AD (ATRAP, ATHENA, ALPHA), to study antihydrogen and test *CPT*
  - e.g., is Lamb shift identical for H and $\overline{\mathrm{H}}$?

- Struggling with difficulty of combining antiprotons with positrons in a Penning trap and winding up in (or near) ground state

Antihydrogen

Antihydrogen

- But over 10 years ago, LEAR PS210 & FNAL E835 produced oodles of $\overline{\mathrm{H}}$!

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ELSEVIER

Physics Letters B 368 (1996) 251–258

Production of antihydrogen

G. Baur[a], G. Boero[b], S. Brauksiepe[a], A. Buzzo[b], W. Eyrich[c], R. Geyer[a], D. Grzonka[a], J. Hauffe[c], K. Kilian[a], M. LoVetere[b], M. Macri[b], M. Moosburger[c], R. Nellen[a], W. Oelert[a], S. Passaggio[b], A. Pozzo[b], K. Röhrich[a], K. Sachs[a], G. Schepers[e], T. Sefzick[a], R.S. Simon[d], R. Stratmann[d], F. Stinzing[c], M. Wolke[a]

[a] *IKP, Forschungszentrum Jülich GmbH, Germany*

[b] *Genoa University and INFN, Italy*

[c] *PI, Universität Erlangen–Nürnberg, Germany*

[d] *GSI Darmstadt, Germany*

[e] *IKP, Universität Münster, Germany*

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Editor: L. Montanet

Abstract

Results are presented for a measurement for the production of the antihydrogen atom $\overline{\mathrm{H}}^0 \equiv \bar{\mathrm{p}}\mathrm{e}^+$, the simplest atomic bound state of antimatter.

A method has been used by the PS210 collaboration at LEAR which assumes that the production of $\overline{\mathrm{H}}^0$ is predominantly mediated by the $\mathrm{e}^+\mathrm{e}^-$-pair creation via the two-photon mechanism in the antiproton–nucleus interaction. Neutral $\overline{\mathrm{H}}^0$ atoms are identified by a unique sequence of characteristics. In principle $\overline{\mathrm{H}}^0$ is well suited for investigations of fundamental CPT violation studies under different forces, however, in our investigations we concentrate on the production of this antimatter object, since so far it has never been observed before.

The production of 11 antihydrogen atoms is reported including possibly 2 ± 1 background signals, the observed yield agrees with theoretical predictions.

Antihydrogen

- But over 10 years ago, LEAR PS210 & FNAL E835 produced oodles of $\overline{H}$!

VOLUME 80, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1998

Observation of Atomic Antihydrogen

G. Blanford,[1] D. C. Christian,[2] K. Gollwitzer,[1] M. Mandelkern,[1] C. T. Munger,[3] J. Schultz,[1] and G. Zioulas[1]

[1] *University of California at Irvine, Irvine, California 92697*

[2] *Fermilab, Batavia, Illinois 60510*

[3] *SLAC, Stanford, California 94309*

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- Formed automatically e.g. in E835 gas-jet target,detected in “parasitic” E862

Antihydrogen

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(Received 26 November 1997)

We report the background-free observation of atomic antihydrogen, produced by antiproton beam with a hydrogen gas jet target in the Fermilab Antiproton Accumula the cross section of the reaction $\overline{p}p \rightarrow \overline{H}e^- p$ for $\overline{p}$ beam momenta between 5203 an be 1.12 ± 0.14 ± 0.09 pb. [S0031-9007(98)05685-3]

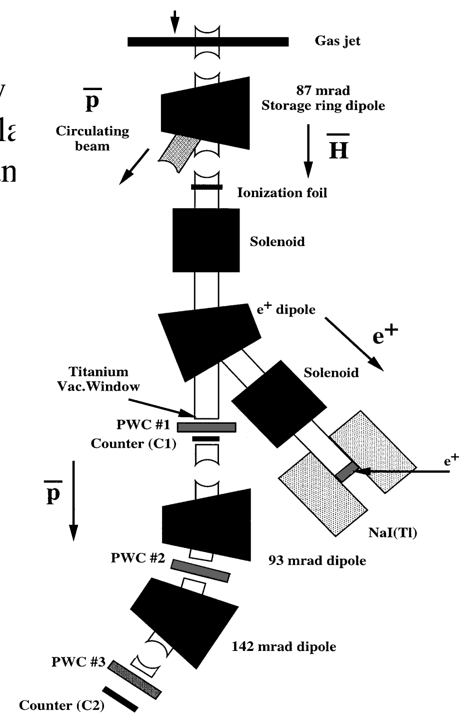

FIG. 1. Experimental apparatus.

- Formed automatically e.g. in E835 gas-jet target, detected in "parasitic" E862

Antihydrogen

- But over 10 years ago, LEAR PS210 & FNAL E835 produced oodles of $\bar{H}$!

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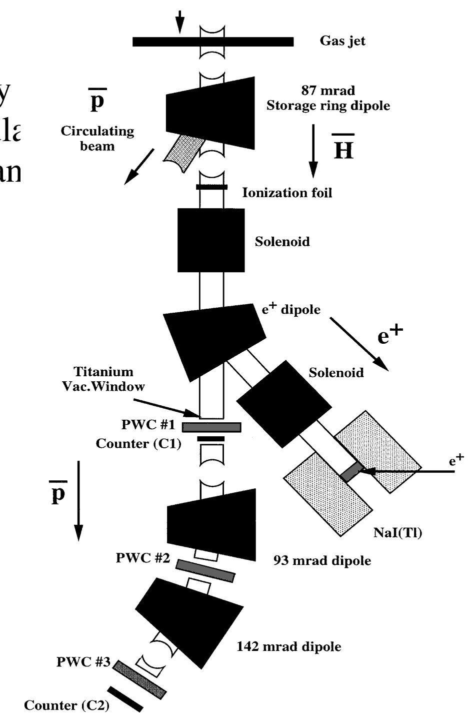

FIG. 1. Experimental apparatus.

- Formed automatically e.g. in E835 gas-jet target,detected in "parasitic" E862
- Cross section grows with E_{beam}, Z_{tgt}

Antihydrogen

- Subsequently worked out technique to measure Lamb shift of relativistic $\overline{\mathrm{H}}$ in flight:

Antihydrogen

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PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Measuring the antihydrogen Lamb shift with a relativistic antihydrogen beam

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(Received 18 December 1997; published 4 May 1998)

We propose an experiment to measure the Lamb shift and fine structure (the intervals $2s_{1/2}-2p_{1/2}$ and $2p_{1/2}-2p_{3/2}$) in antihydrogen. A sample of 10 000 antihydrogen atoms at a momentum of 8.85 GeV/c suffices to measure the Lamb shift to 5% and the fine structure to 1%. Atomic collisions excite antihydrogen atoms to states with $n=2$; field ionization in a Lorentz-transformed laboratory magnetic field then prepares a particular $n=2$ state, and is used again to analyze that state after it is allowed to oscillate in a region of zero field. This experiment is feasible at Fermilab. [S0556-2821(98)04711-0]

Antihydrogen

- Further parasitic running appears feasible
- Hope to install high-*Z* foil operable in Antiproton Accumulator beam halo at upcoming shutdown
- Can then assemble Lamb-shift apparatus (magnets, laser, detectors) and begin shakedown and operation

- From D. Christian:

CPT test using relativistic antihydrogen

- Antihydrogen is produced in the gas-jet target - exits the Accumulator in the ground state.
  - 99 antihydrogen atoms were observed by E862 with 0 background.
- The atoms enter a 7kG magnet and a large fraction are excited to N=2 long-lived Stark state by laser light.
- Atoms exit magnet & pass through a field-free region, then enter a second magnet with field 6-8 kG. The mixture of N=2 Stark states in the second magnet depends on the time spent in the field-free region, the fine structure, and the Lamb shift.
- Distribution of field ionization in the second magnet reflects probability of being in each of the three N=2 Stark states.
- Monte Carlo —> an experiment in which 100 atoms exit the first magnet in N=2,L will yield a 1% measurement of the fine structure and a 5% measurement of the Lamb shift. Assuming that only the 2S level is shifted by a CPT violating force, the 1σ sensitivity is 50 parts per billion of the 2S binding energy.

Antimatter Gravity

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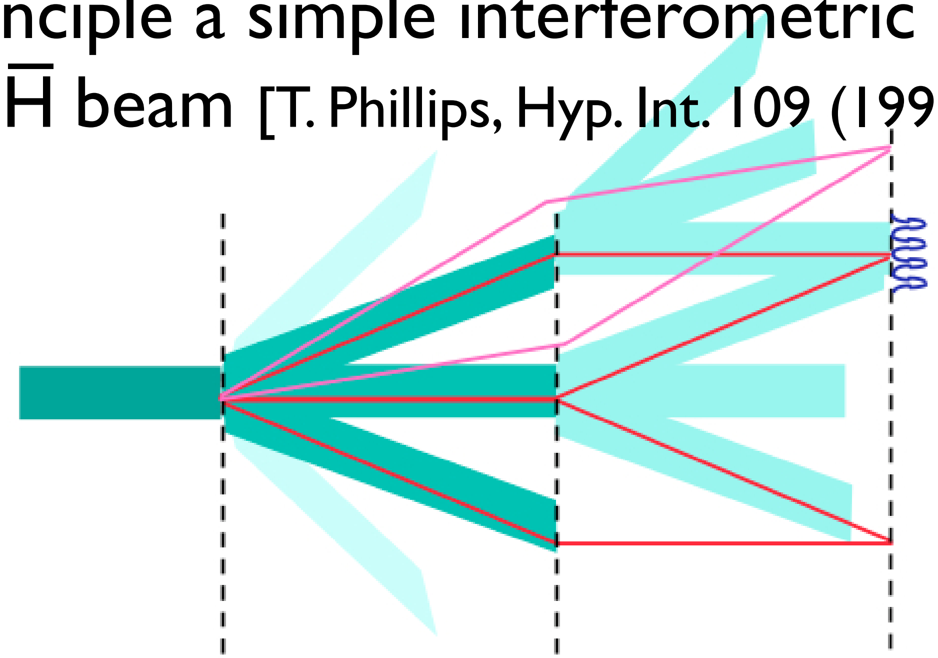

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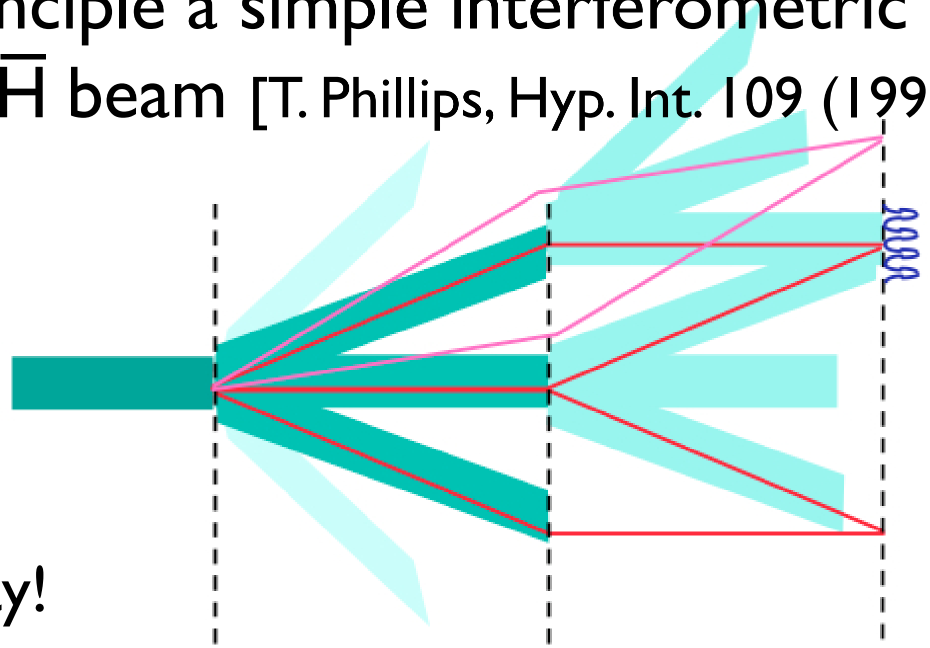

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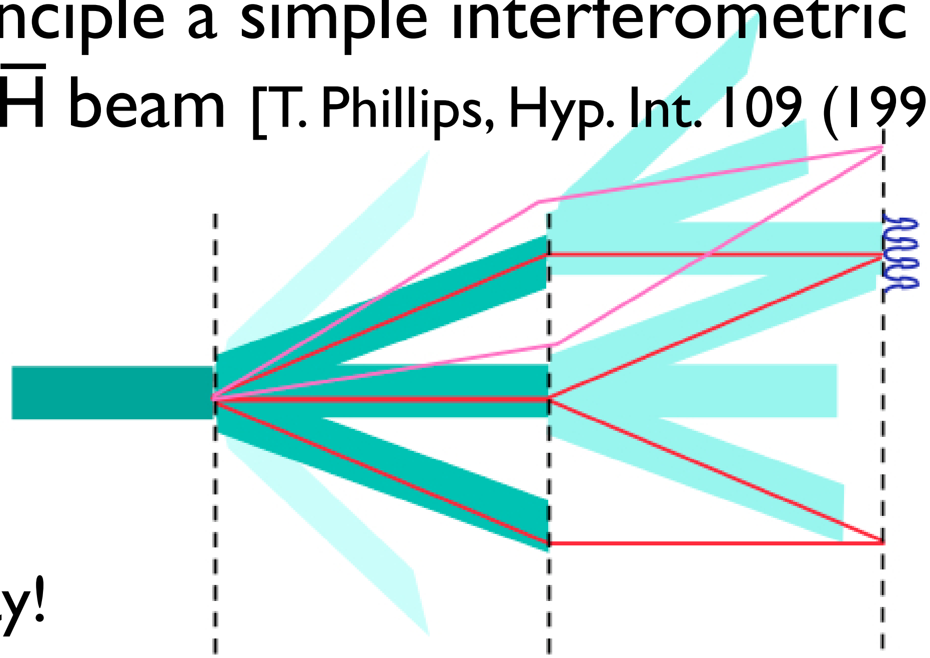

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⟶ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

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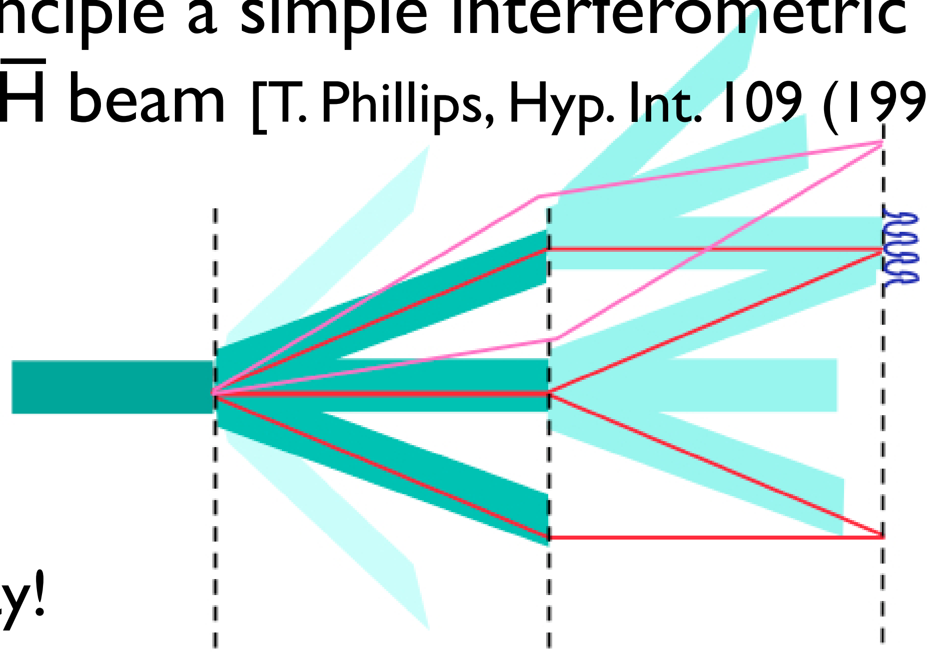

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→ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

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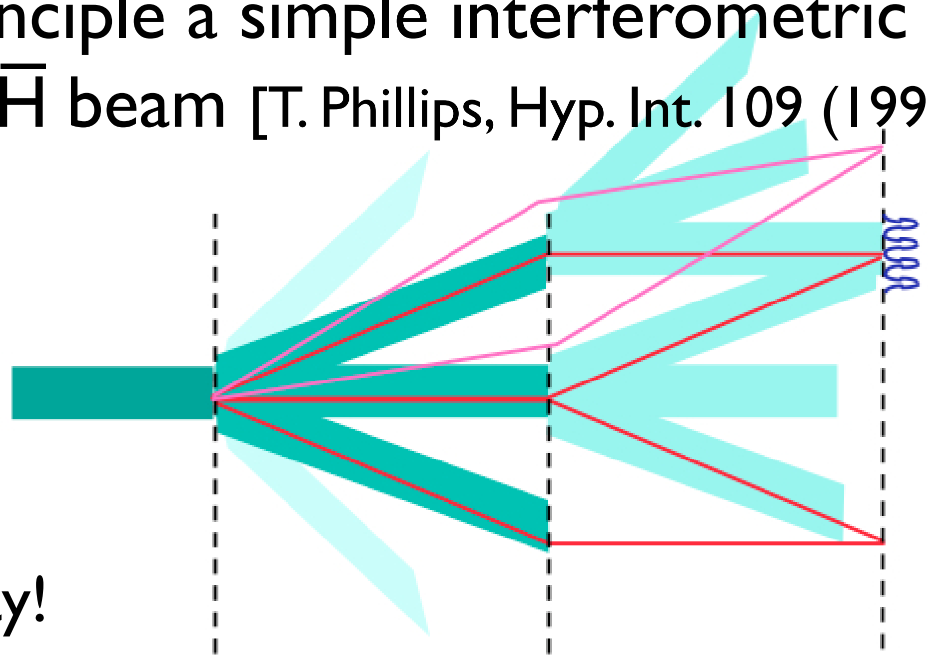

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→ $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy

→ $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

→ tests for possible "5th forces"

Antimatter Gravity

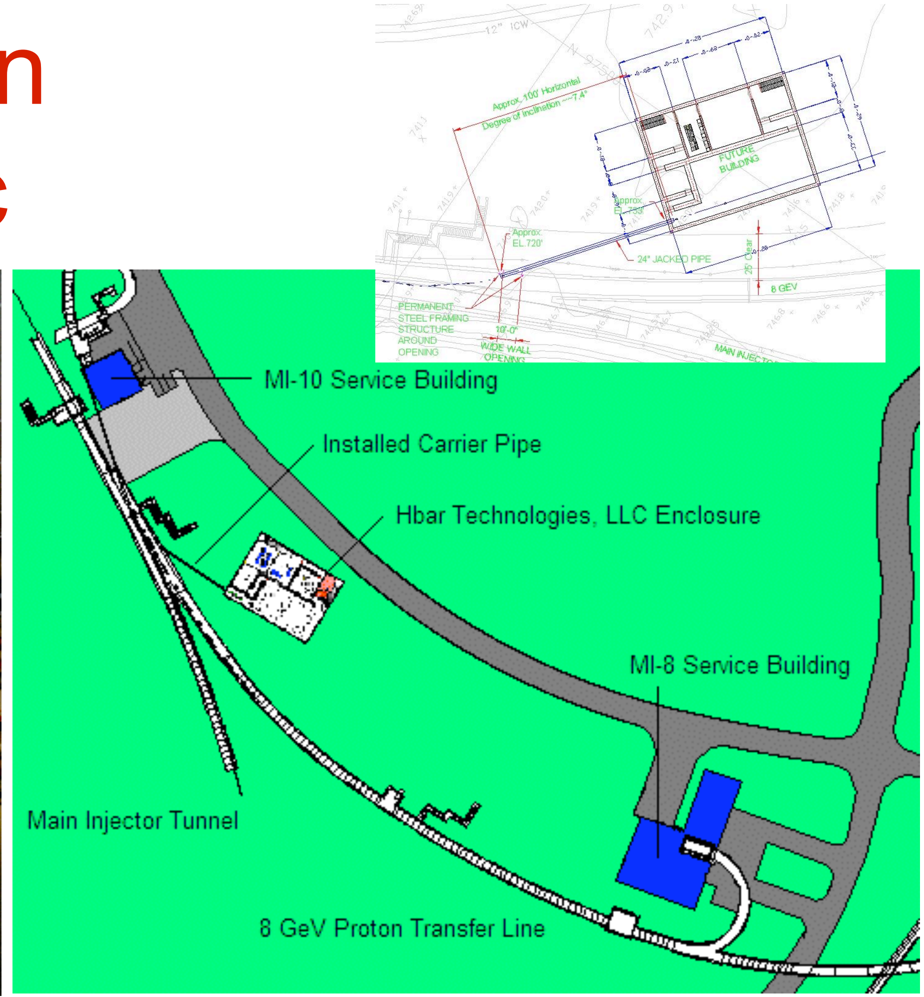
- Requires development of deceleration techniques from 8 GeV to <20 keV:
  - MI from 8 GeV to $\lesssim$ 400 MeV (TBD), then "reverse linac," then degrade?
  - efficiency $\gtrsim 10^{-4}$ looks feasible
    $\Rightarrow 10^{-4}$ $\bar{g}$ meas't in ~ month's dedicated running
  - eventually, small synchrotron by HBar Tech → eff ~ 1
- Requires completion of antiproton deceleration/ extraction facility planned for Hbar Technologies

HBAR Technologies, LLC

Making Antimatter Matter®

1275 W. Roosevelt Rd., Suite 130, West Chicago IL, 60185
www.hbartech.com

MI Deceleration Below 1 GeV/c



- From G. Jackson:

HBAR Technologies, LLC
Making Antimatter Matter®

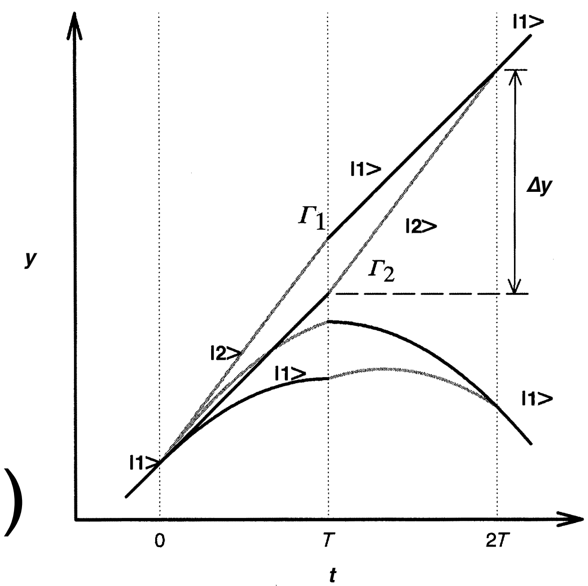
1275 W. Roosevelt Rd., Suite 130, West Chicago IL, 60185
www.hbartech.com

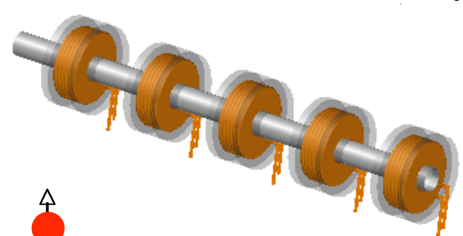
The HiPAT trap

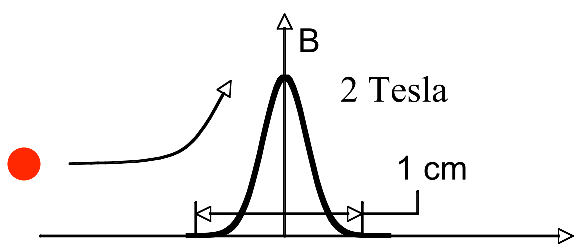
- Designed to hold 1E12 antiprotons
- Designed to be portable
- Traditional super-conducting solenoid requiring liquid helium for the superconductors and liquid nitrogen for the heat shield
- Good vacuum lifetime
- Comes with proton and H- linacs for commissioning
- Still at NASA MSFC

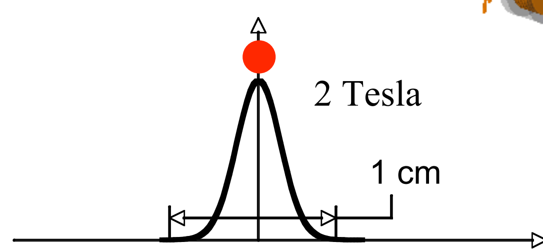
Antimatter Gravity

- "Ultimate" measurement:
  - use lasers à la S. Chu
  - slow down and trap the $\overline{\text{H}}$ atoms using "coilgun" (M. Raizen)
  - low-field seekers are repulsed by magnetic field









  - estimate 10^{-9} $\overline{g}$ measurement feasible

Is There an Interested Collaboration?

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Version 1.9
February 4, 2009

Letter of Intent:
Antimatter Gravity Experiment (AGE) at Fermilab

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*Contact person; email: Thomas.Phillips@duke.edu.
*Contact person; email: kaplan@iit.edu.

Abstract

Fermilab's unique ability to accumulate large numbers of antiprotons makes it possible to directly measure the gravitational force on antimatter for the first time. Such a measurement will be a fundamental test of gravity in a new regime,

Is There an Interested Collaboration?

P-986 Letter of Intent:

Medium-Energy Antiproton Physics at Fermilab

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E. Craig Dukes
University of Virginia, Charlottesville, Virginia 22903, USA

February 5, 2009

Summary

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- Best experiment ever on hyperons, charm, and charmonia may soon be feasible at Fermilab

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And, please, help spread the word!

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(See http://capp.iit.edu/hep/pbar)

Some HyperCP Publications:

- L. C. Lu *et al.*, "Measurement of the asymmetry in the decay $\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \overline{p}\pi^+ K^+$," Phys. Rev. Lett. **96**, 242001 (2006).
- D. Rajaram *et al.*, "Search for the Lepton-Number-Violating Decay $\Xi^- \to p\mu^-\mu^-$," Phys. Rev. Lett. **94**, 181801 (2005).
- C. G. White *et al.*, "Search for Delta $\Delta S = 2$ Nonleptonic Hyperon Decays," Phys. Rev. Lett. **94**, 101804 (2005).
- H. K. Park *et al.*, "Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$," Phys. Rev. Lett. **94**, 021801 (2005).
- M. Huang *et al.*, "New Measurement of $\Xi^- \to \Lambda\pi^-$ Decay Parameters," Phys. Rev. Lett. **93**, 011802 (2004);
- M. J. Longo *et al.*, "High-Statistics Search for the $\Theta^+(1.54)$ Pentaquark," Phys. Rev. D **70**, 111101(R) (2004);
- T. Holmstrom *et al.*, "Search for *CP* Violation in Charged-Ξ and Λ Hyperon Decays," Phys. Rev. Lett. **93**, 262001 (2005);
- Y. C. Chen *et al.*, "Measurement of the Alpha Asymmetry Parameter for the $\Omega^- \to \Lambda K^-$ Decay," Phys. Rev. D **71**, 051102(R) (2005);
- L. C. Lu *et al.*, "Observation of Parity Violation in the $\Omega^- \to \Lambda K^-$ Decay," Phys. Lett. B **617**, 11 (2005).
- R. A. Burnstein *et al.*, "HyperCP: A High-Rate Spectrometer for the Study of Charged Hyperon and Kaon Decays," Nucl. Instrum. Methods A **541**, 516 (2005).

Backup

Table 5: Summary of predicted hyperon CP asymmetries.

Asymm.	Mode	SM	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[68]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 0.5 \times 10^{-4}$	$\leq 1.9 \times 10^{-3}$	[69]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K,\ \Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[36]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4}$ *	[35]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[36]

*Once they are taken into account, large final-state interactions may increase this prediction

Backup

- Some Hyperon CP references:

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